Identification of infrastructure related risk factors

Deliverable 5.1

SafetyCube

Identification of infrastructure related risk factors

Work package 5, Deliverable 5.1

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Table of Contents

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Executive summary

The present Deliverable (D5.1) describes the **identification and evaluation of infrastructure related risk factors**. It outlines the results of Task 5.1 of WP5 of SafetyCube, which aimed to identify and evaluate infrastructure related risk factors and related road safety problems by (i) presenting a taxonomy of infrastructure related risks, (ii) identifying "hot topics" of concern for relevant stakeholders and (iii) evaluating the relative importance for road safety outcomes (crash risk, crash frequency and severity etc.) within the scientific literature for each identified risk factor. To help achieve this, Task 5.1 has initially exploited current knowledge (e.g. existing studies) and, where possible, existing accident data (macroscopic and in-depth) in order to identify and rank risk factors related to the road infrastructure. This information will help further on in WP5 to identify countermeasures for addressing these risk factors and finally to undertake an assessment of the effects of these countermeasures.

In order to develop **a comprehensive taxonomy of road infrastructure-related risks**, an overview of infrastructure safety across Europe was undertaken to identify the main types of road infrastructure-related risks, using key resources and publications such as the European Road Safety Observatory (ERSO), The Handbook of Road Safety Measures (Elvik et al., 2009), the iRAP toolkit and the SWOV factsheets, to name a few. The taxonomy developed contained **59 specific risk factors** within 16 general risk factors, all within 10 infrastructure elements.

In addition to this, **stakeholder consultations in the form of a series of workshops were undertaken to prioritise risk factors ('hot topics')** based on the feedback from the stakeholders on which risk factors they considered to be the most important or most relevant in terms of road infrastructure safety. The stakeholders who attended the workshops had a wide range of backgrounds (e.g. government, industry, research, relevant consumer organisations etc.) and a wide range of interests and knowledge. The identified 'hot topics' were ranked in terms of importance (i.e. which would have the greatest effect on road safety). SafetyCube analysis will put the greatest emphasis on these topics (e.g. pedestrian/cyclist safety, crossings, visibility, removing obstacles).

To evaluate the scientific literature, a **methodology was developed in Work Package 3 of the SafetyCube project. WP5 has applied this methodology** to road infrastructure risk factors. This uniformed approach facilitated systematic searching of the scientific literature and consistent evaluation of the evidence for each risk factor. The method included a **literature search strategy, a 'coding template' to record key data and metadata from individual studies, and guidelines for summarising the findings** (Martensen et al, 2016b). The main databases used in the WP5 literature search were Scopus and TRID, with some risk factors utilising additional database searches (e.g. Google Scholar, Science Direct). Studies using crash data were considered highest priority. Where a high number of studies were found, further selection criteria were applied to ensure the best quality studies were included in the analysis (e.g. key meta-analyses, recent studies, country origin, importance).

Once **the most relevant studies were identified for a risk factor, each study was coded** within a template developed in WP3. Information coded for each study included road system element, basic study information, road user group information, study design, measures of exposure, measures of outcomes and types of effects. The information in the coded templates will be included in the relational database developed to serve as the main source ('back end') of the Decision Support

System (DSS) being developed for SafetyCube. Each risk factor was assigned a secondary coding partner who would carry out the control procedure and would discuss with the primary coding partner any coding issues they had found.

Once all studies were coded for a risk factor, **a synopsis was created, synthesising the coded studies** and outlining the main findings in the form of meta-analyses (where possible) or another type of comprehensive synthesis (e.g. vote-count analysis). Each synopsis consists of three sections: a 2 page summary (including abstract, overview of effects and analysis methods); a scientific overview (short literature synthesis, overview of studies, analysis methods and analysis of the effects) and finally supporting documents (e.g. details of literature search and comparison of available studies in detail, if relevant).

To enrich the background information in the synopses, **in-depth accident investigation data** from a number of sources across Europe (i.e. GIDAS, CARE/CADaS) was sourced. Not all risk factors could be enhanced with this data, but where it was possible, the aim was to provide further information on the type of crash scenarios typically found in collisions where specific infrastructure-related risk factors are present. If present, this data was included in the synopsis for the specific risk factor.

After undertaking the literature search and coding of the studies, it was found that for some risk factors, not enough detailed studies could be found to allow a synopsis to be written. Therefore, the revised number of specific risk factors that did have a synopsis written was 37, within 7 infrastructure elements. Nevertheless, the coded studies on the remaining risk factors will be included in the database to be accessible by the interested DSS users. At the start of each synopsis, **the risk factor is assigned a colour code, which indicates how important this risk factor is** in terms of the amount of evidence demonstrating its impact on road safety in terms of increasing crash risk or severity. The code can either be Red (very clear increased risk), Yellow (probably risky), Grey (unclear results) or Green (probably not risky). In total, eight risk factors were given a Red code (e.g. traffic volume, traffic composition, road surface deficiencies, shoulder deficiencies, workzone length, low curve radius), twenty were given a Yellow code (e.g. secondary crashes, risks associated with road type, narrow lane or median, roadside deficiencies, type of junction, design and visibility at junctions) seven were given a Grey code (e.g. congestion, frost and snow, densely spaced junctions etc.). The specific risk factors given the red code were found to be distributed across a range of infrastructure elements, demonstrating that the greatest risk is spread across several aspects of infrastructure design and traffic control. However, four 'hot topics' were rated as being risky, which were 'small work-zone length', 'low curve radius', 'absence of shoulder' and 'narrow shoulder'.

Some **limitations** were identified. Firstly, because of the method used to attribute colour code, it is in theory possible for a risk factor with a Yellow colour code to have a greater overall magnitude of impact on road safety than a risk factor coded Red. This would occur if studies reported a large impact of a risk factor but without sufficient consistency to allocate a red colour code. Road safety benefits should be expected from implementing measures to mitigate Yellow as well as Red coded infrastructure risks. Secondly, findings may have been limited by both the implemented literature search strategy and the quality of the studies identified, but this was to ensure the studies included were of sufficiently high quality to inform understanding of the risk factor. Finally, due to difficulties of finding relevant studies, it was not possible to evaluate the effects on road safety of all topics listed in the taxonomy.

The **next task of WP5** is to begin identifying measures that will counter the identified risk factors. Priority will be placed on investigating measures aimed to mitigate the risk factors identified as Red. The priority of risk factors in the Yellow category will depend on why they were assigned to this category and whether or not they are a hot topic.

List of Abbreviations

AADT	Annual average daily traffic
ADAS	Advanced driver assistance systems
ANOVA	Analysis of Variance
ASECAP	Association Europeenne des Concessionnaires d'Autoroutes et d'Ouvrages a Peage
BaST	Federal Highway Research Institute
BRRC	Belgian Road Research Center
CaDaS	Common Accident Data Set
CARE	Community database on Accidents on the Roads in Europe
CEDR	Conference of European Directors of Roads
CMF	Crash Modification Factor
CPM	Crash Prediction Model
DSS	Decision Support System
EC-INEA	European Commision- Innovation and Networks Executive Agency
EC-DG-MOVE	European Commision Directorate-General for Mobility and Transport
ERSO	European Road Safety Observatory
ETSC	European Transport Safety Council
EURORAP	The European Road Assessment Programme
FAT	German Association for Research in Automobile Technology (FAT)
FIA	Federation Internationale de l'Automobile
GIDAS	German In-Depth Accident Study
HGV	Heavy Goods Vehicle
iRAP	International Road Assessment Programme
IRTAD	International Traffic Safety Data and Analysis Group
ISA	Intelligent Speed Adaptation
ITS	Intelligent Transportation Systems
LAB	Laboratory of Accidentology, Biomechanics and Human Behaviour
MHH	Hanover Medical School (MHH)
OECD	Organisation for Economic Co-operation and Development
POLIS	European cities and regions cooperating on sustainable mobility
PRACT	Predicting road accidents – a transferable methodology across Europe
ROR	Run-off-road
ROSEBUD	Road safety and environmental benefit-cost and cost-effectiveness analysis for use in decision Making
SPI	Safety Performance Indicator
SUPREME	SUmmary and publication of best Practices in Road safety in the Eu MEmber States
SWOV	Stichting Wetenschappelijk Onderzoek Verkeersveiligheid
TRID	Transport Research International Documentation
VMS	Variable Message Signs
VRU	Vulnerable Road User(s)
WP	Work Package

1 Introduction

This chapter describes the overall project and the purpose of this deliverable.

1.1 SAFETYCUBE

Safety CaUsation, Benefits and Efficiency (SafetyCube) is a European Commission supported Horizon 2020 project with the objective of **developing an innovative road safety Decision Support System (DSS)** that will enable policy-makers and stakeholders to select and implement the most appropriate strategies, measures and cost-effective approaches to reduce casualties of all road user types and all severities.

SafetyCube aims to:

1. Develop new analysis methods for (a) Priority setting, (b) Evaluating the effectiveness of measures (c) Monitoring serious injuries and assessing their socio-economic costs (d) Cost-benefit analysis taking account of human and material costs
2. Apply these methods to safety data to identify the key accident causation mechanisms, risk factors and the most cost-effective measures for fatally and seriously injured casualties
3. Develop an operational framework to ensure the project facilities can be accessed and updated beyond the completion of SafetyCube
4. Enhance the European Road Safety Observatory and work with road safety stakeholders to ensure the results of the project can be implemented as widely as possible

The core of the project is **a comprehensive analysis of accident risks and the effectiveness and cost-benefit of safety measures focusing on road users, infrastructure, vehicles and injuries framed within a systems approach** with road safety stakeholders at the national level, EU and beyond having involvement at all stages.

1.1.1 Work Package 5

The objective of the Work Package (WP) is the in-depth understanding of infrastructure related accident causation factors and the identification and evaluation of the most appropriate related measures. **This WP will exploit a large amount of existing accident data (macroscopic and in-depth) and knowledge (e.g. existing studies) in order:**

i. to identify and rank risk factors related to the road infrastructure,
ii. to identify measures for addressing these risk factors,
iii. to assess the effects of measures.

WP5 will thus contribute to all the objectives of SafetyCube, as listed in section 1.1 above, from a road infrastructure viewpoint. WP5 includes **four distinct and complementary Tasks**, as follows:
Task 5.1. Identification of infrastructure related risk factors
Task 5.2. Identification of safety effects of infrastructure related measures
Task 5.3. Evaluation of key infrastructure related road safety measures
Task 5.4. Inventory of road infrastructure safety measures

More specifically, the WP starts with the creation of an exhaustive list of risk factors and road safety measures specific to the road infrastructure (**taxonomies**). For all these elements, a set of basic pieces of information are available within the existing literature, e.g. a general description, a rough assessment of the safety effects (high / low or range of values, if known) and the related costs (high /

low, or unit costs if known), other effects (mobility, environmental etc.). The stakeholders' consultation taking place in WP 2 is an additional source of basic information on the risk factors and measures.

This exhaustive list has been examined together with WP3 and WP8, in order to make a selection of risk factors and measures that will be analysed and evaluated. For the selected risk factors and measures, the **methodologies and guidelines developed in WP3** (Martensen et al., 2017) are implemented and tested in the WP5 analyses. At the same time, care is taken – under the supervision of WP8 - that the conceptual framework of the analyses is consistent with the "systems" approach, that the combined effect of risks and measures related to more than one component of the system (user, infrastructure, vehicle) is taken into account. Eventually, the inventory will include research results on numerous risk factors and measures, together with an assessment of the quality of the data / study methods from which the results are obtained.

Overall, **a mixture of methods and data sources** have been utilised followingthe WP3 methodologies:

- existing and new data sources (macroscopic or in-depth) are used for carrying out original analyses.
- existing studies are examined for carrying out meta-analyses or other types of analysis allowing for comprehensive syntheses of results (e.g. vote-count analysis), to estimate the effects of risk factors and the efficiency of road safety measures.

Eventually, WP5 will create an **inventory of evaluated road safety risks and measures** related to the road infrastructure, with results from accident risk factors analysis and measures cost-efficiency assessment, to be integrated in the DSS system of WP8.

1.2 PURPOSE AND STRUCTURE OF THIS DELIVERABLE

This deliverable reports on the work in Task 5.1. This addresses one of the main objectives of WP5 by contributing towards the creation of an inventory of estimates of risk factors and safety effects for road infrastructure. The current report focuses on identifying and evaluating infrastructure related risk factors and related road safety problems by:

1. **Presenting a taxonomy of road infrastructure related risks**

This taxonomy provides a comprehensive overview of the infrastructure risk factors identified as being road safety problems influencing crash risk.

2. **Identifying "hot topics" of concern for relevant stakeholders**

Thorough consultation with relevant stakeholder groups the risk factors of greatest interest have been identified.

3. **Evaluating the relative importance for crash outcomes (risk, frequency, severity) for each identified risk factor.**

As part of Task 5.1 the SafetyCube methodology is applied to existing scientific literature considering each infrastructure risk factor. The evidence has been evaluated and each risk factor allocated a colour code demonstrating the relative impact on road safety and an abstract summarising the each risk factor. This methodology advances the current state of the art. Although existing repositories of safety measures exist (e.g. CMF clearing house; Australian Clearing house) these only consider infrastructure measures. The DSS of SafetyCube has a much broader scope than these previous repositories, or for example the Handbook of Road Safety Measures (Elvik et al., 2009).

1.2.1 Report structure

This report has five chapters. The **first (current) chapter** provides background information about the SafetyCube project and the current Work Package. **Chapter 2** introduces the concept of infrastructure risks and details how they have been identified. **Chapter 3** details the central SafetyCube methodology which has been applied for identifying and evaluating infrastructure related risk factors. **Chapter 4** considers each infrastructure risk factor in turn, presenting a colour code indicating the level of evidence for risk of this particular factor, with an abstract summarising the findings. **Chapter 5** concludes the report, summarizing the main findings and detailing the next steps. The main results of deliverable 5.1 include a variety of systematically analysed risk factors, documented in risk factor 'synopses' which will be incorporated into the Safety Cube DSS and linked to corresponding road safety measures and cost-benefit-analyses of certain measures. As the synopses are very comprehensive, they form individual documents appended to this one and will be made available separately within the DSS when it is launched.

2 Infrastructure Risk Factors

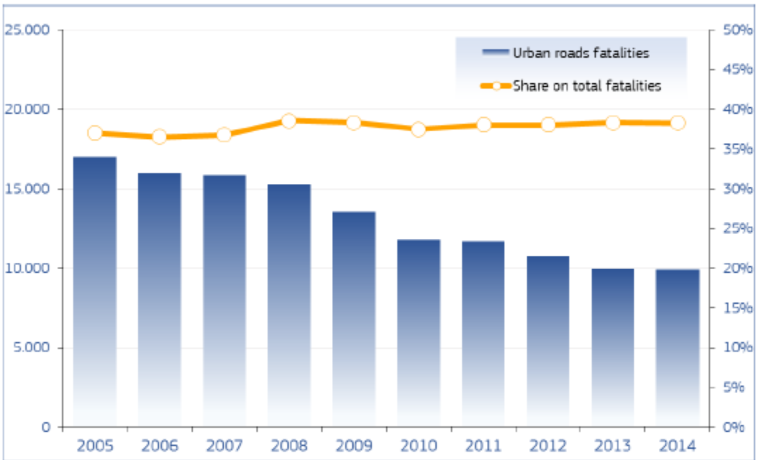
This chapter provides an overview of infrastructure safety across the EU, on the basis of macroscopic data (i.e. the CARE database[1]). The taxonomy of infrastructure risk factors is presented and how these were systematically identified. Risk factors were also considered as part of stakeholder consultation to identify the topics of greatest interest ('hot topics').

2.1 OVERVIEW OF INFRASTRUCTURE SAFETY IN EUROPE

The European Union (EU) has made substantial progress in improving road safety and reducing traffic fatalities. In the decade up to 2010, the number of fatalities reduced by 45% and the total number injured reduced by 30% (EuroStat, 2012). To further reduce the road toll it is necessary to understand the risks involved. Crash data, such as that from CARE database (with the CADaS set of common definitions and record layout) is a rich source of information which can be used to better understand the role of road infrastructure in road safety.

One of the most critical factors affecting road safety outcomes is **road infrastructure and environment** (e.g. road type, geometrical design, traffic control, lighting and weather conditions, etc.) (Elvik et al., 2009). The European Commission and the **European Road Safety Observatory (ERSO)** release annual reports based of the CARE/ CADaS data and which include crash trends and developments related to road infrastructure such as crashes road type.

Figure 1 shows the total number of fatalities within **urban areas** in all EU countries for the years 2005 to 2014, as well as the proportion of all fatalities that occurred within urban areas. It is observed that although the number of fatalities within urban areas is reduced, the proportion has slightly increased (ERSO, 2016a). Moreover, it is evident that fatalities inside urban areas represent a considerable portion of total fatalities.



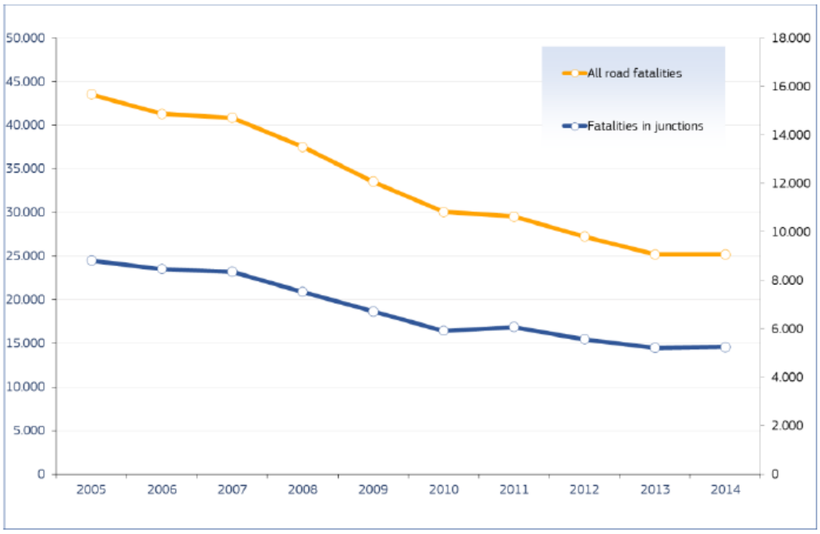
Source: CARE database, data available in May 2016

Figure 1: Number of urban road fatalities and percentage on all road fatalities, 2005-2014.

[1] CARE is a Community database on road accidents resulting in death or injury. The major difference between CARE and most other existing international databases is the high level of disaggregation, i.e. CARE comprises detailed data on individual accidents as collected by the Member States on the basis of the CADaS set of common definitions and records layout. For more information see http://ec.europa.eu/transport/road_safety/specialist/statistics/index_en.htm.

On the other hand, another recent ERSO report (ERSO, 2016b) shows that almost 26,000 people were killed in road accidents on **motorways** in European Union countries between 2005 and 2014 (7% of all road fatalities). Spain had the highest percentage of fatalities on motorways in 2014 in the EU (17%), followed by Belgium (15%), Slovenia (13%) and the Netherlands (12%). By contrast, the lowest proportion of fatalities occurring on motorways were in Romania (1%) and Poland (2%) - these percentages partly reflect the length of motorways and the traffic of motorways in each country, as they are not corrected for this proxy exposure factor. For instance, if there are relatively few motorways carrying a fraction of the total trips made on the network, few crashes are expected on motorways. Conversely, in countries where the majority of the trips (veh-kms) are made on motorways, although the absolute numbers are high, crash risk rates are low.

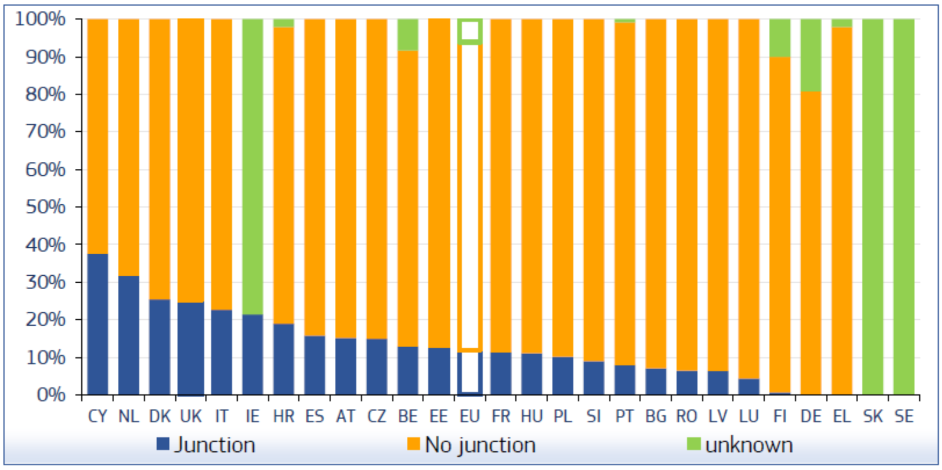
Junctions are critical infrastructure elements in both urban and rural areas. In 2014, about 26,000 people were killed in road accidents in EU countries; at least 5,000 of whom were killed in road accidents that occurred at junctions (ERSO, 2016c). Fatalities at junctions and total fatalities are showing a constant reduction since 2005, but fatalities at junctions decrease at a lower rate than total fatalities, as shown in **Figure 2**.



Source: CARE database, data available in May 2016.

Figure 2: Number of junction fatalities and all road fatalities, EU, 2005-2014

Figure 3 shows the distribution of fatalities in **rural areas** according to location on the road segment (i.e. at junction, not at junction) in the EU countries (ERSO, 2016d). While the EU average percentage of fatalities at junctions in rural areas is low (12%), a number of countries, such as Cyprus, the Netherlands, Denmark and the UK have considerably higher percentages. Again, countries with denser road networks will have more crashes at junctions.



Source: CARE database. data available in Mav 2016

Figure 3: Distribution of fatalities in rural areas by country and "junction", 2014 or latest available year

Finally, looking at the effect of road environment factors, **Table 1** illustrates the distribution of fatalities on roads outside urban areas, urban areas and motorways by **lighting conditions** (ERSO, 2016d).

Table 1: Distribution of fatalities on Roads outside urban areas, urban areas and motorways by lighting conditions, EU, 2014 or latest available year. Source: CARE database, data available in May 2016.

Lighting conditions	Outside urban areas	Urban areas	Motorways	Total
Daylight	52.5%	45.5%	42.3%	49.1%
Twilight	4.9%	4.9%	5.0%	4.9%
Darkness - no street lights	18.2%	5.2%	14.9%	12.8%
Darkness - street lights lit	3.5%	20.9%	5.1%	10.3%
Darkness - street lights unknown	3.9%	3.2%	8.1%	4.0%
Darkness - street lights unlit	2.0%	1.3%	3.5%	1.9%
Unknown conditions	14.9%	18.9%	21.1%	16.9%

These results show that the percentage of fatalities in daylight conditions is slightly higher on rural roads (52.5%) than urban roads and motorways. 28% of fatalities on the rural roads occurred at night (all "darkness" variables combined), this percentage being lower than on urban roads (31%) and also lower than on motorways (32%). On roads outside urban areas, about 18% of the fatalities happened in darkness without any street lighting. However, the proportions collected under the different categories of "darkness" may be distorted because of the high percentage of "unknown" values in the variable describing whether the street light was lit or unlit. Moreover, the difference in the duration of daylight between European countries is likely to affect the results.

Another factor related to the road environment with a well known effect on accident risk is **weather conditions**, closely linked to seasonality and daylight duration. According to ERSO data (ERSO, 2016e), the great majority of fatalities (83%) occur in dry weather conditions. Nevertheless, in order to illustrate the geographical and seasonal components involved, the distribution of fatalities by weather conditions is shown in **Figure 4**, which compares the distributions in Spain and three EU Nordic countries. The proportion of fatalities in dry conditions is only slightly greater in Spain (86% compared with 85%), but the proportion in rain or snow is predictably much lower.

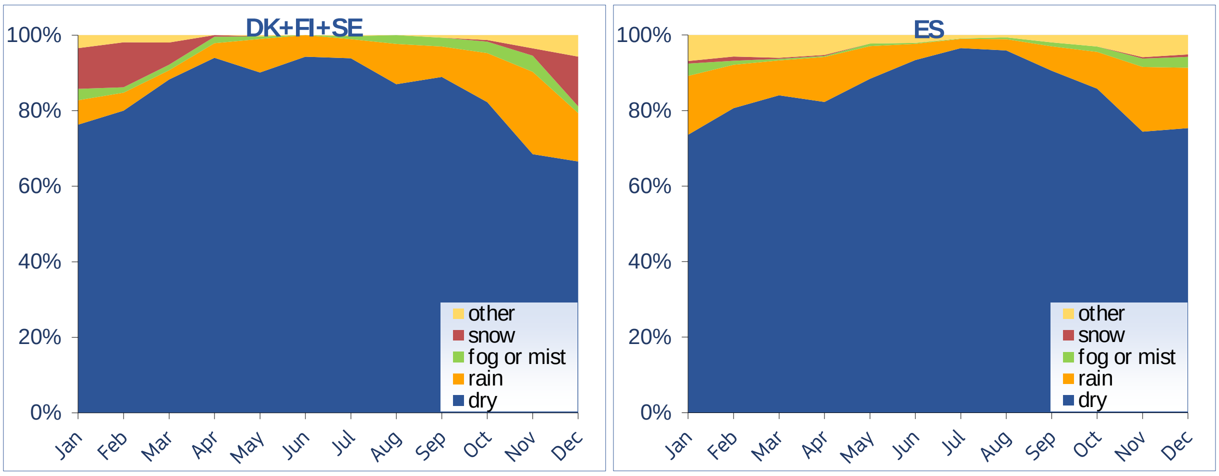


Figure 4: Distribution of fatalities by country, month and weather condition, 2010-2014 or latest available year

The above data suggests that there are indications and patterns of **road safety problems related to the road infrastructure and environment** in the European countries, which raises the need for further insight on the identification of critical infrastructure risk factors and their impact on road safety outcome indicators - which is not possible through the analysis of the available macroscopic data alone. SafetyCube WP5 aims to **identify, analyse in-depth and rank the specific road network management, design, traffic control and environmental factors** that affect road safety outcomes. This type of analysis may shed light on the impacts of specific infrastructure risk factors, and eventually the causation of road accidents in terms of road infrastructure.

2.2 WHAT IS A RISK FACTOR?

Within the SafetyCube project **'risk factor' refers to any factor that contributes to the occurrence or the consequence of road accidents**. Risk factors can have a direct influence on the risk of an accident occurring, on the consequences of the accident (severity), or more indirectly by influencing a Safety Performance Indicator (SPI). All elements of the road system are potential crash risk factors. WP5 and this report deal with risk factors that are related to the design and layout of the road infrastructure.

2.3 TAXONOMY OF INFRASTRUCTURE RISK FACTORS

The first step in order to be able to identify and rank infrastructure related risk factors in terms of their impact on accident causation was the development of **a taxonomy**. The aim of creating a taxonomy is to identify the relevant topics covering all aspects of infrastructure and road environment risk factors, and structure them in a meaningful way (e.g. general topics, specific topics), **to serve as the back-bone of the analyses**. Starting with the creation of a comprehensive list of risk factors specific to the road infrastructure, on the basis of several key publications, relevant information was sought on their general description, the related risk mechanisms, and a rough assessment of the safety effects (high / low or range of values, if known).

In order to do so, existing studies on infrastructure related risk factors were thoroughly reviewed. This included several **key resources and publications** analysing or comparing infrastructure risk factors and measures, such as:

- **ERSO** web-text on infrastructure (http://ec.europa.eu/transport/road_safety/specialist/erso/pdf/safety_issues/road_safety_measures/01-roads_en.pdf),
- **The Handbook of Safety Measures**,
- **CEDR** Report on 'Cost-Effective Infrastructure Investments',
- **ROSEBUD** Handbook,
- **SUPREME** Handbook,
- **Highway Safety Manual**,
- **OECD/ITF** report on 'Sharing Road Safety',
- **PRACT** research project (EU repository of infrastructure CMFs),
- **iRAP** toolkit and related publications ,
- **SWOV** fact-sheets (http://www.swov.nl/UK/Research/factsheets.htm).

The initial list of risk factors was then examined on the basis of the methodological framework developed in WP3 and the systems approach developed in WP8, in order to make the **final selection and a meaningful classification** of risk factors that would be analysed, ranked and evaluated in terms of their impact on accident causation. The WP5 partners' experience with infrastructure risk research also contributed to the adjustment and optimisation of the list. Emphasis was put on **four "hot topics",** which were initially considered as such on the basis of international experience, from the project Technical Annex (developed since the project proposal phase):

- road safety management,
- self-explaining and forgiving roads,
- ITS applications,
- urban safety measures,

'Hot topics' can be considered as a selection of topics among those which have attracted particular attention by road safety researchers and stakeholders as critical areas for action and / or further research in recent scientific and policy dicuments. These havetherefore been given particular emphasis and priority in the SafetyCube analysis. Of course, the above list of 'hot topics' is not exhaustive and may need adjustment during the project on the basis of new developments internationally, and / or feedback from stakeholders.

More specifically, the stakeholder's consultation taking place in WP2 was an additional source of basic information for the finalisation of the taxonomy, and particularly the selection of 'hot topics'. For that reason, 3 workshops were carried out; June 2015, Brussels; October 2015, Ljubljana; February 2016, Brussels. More details are presented in the next section (2.3).

Eventually, **59 specific risk factors within 16 general risk factors, all within 10 infrastructure elements,** (see Tables 2-9)_have been identified by means of a thorough literature review and assessment of existing road infrastructure safety areas and taxonomies.In particular, a hierarchical taxonomy was created, with infrastructure elements (i.e. general topics) including several general risk factors, and in several cases each general risk factor may include many specific risk factors (see Tables 2-9).

The **infrastructure types** covered in the SafetyCube taxonomy include:

- Freeway segments.
- Interchanges (including speed change lanes, ramp segments, crossroad ramp terminals).
- Rural road segments.
- Rural junctions (including rail-road crossings).
- Urban road segments.
- Urban junctions.

Several risk factors may concern more than one type of infrastructure.

The tables below (**Table 2** to **Table 9**) illustrate the entire taxonomy of risk factors utilised in WP5 of the SafetyCube project. General categories of infrastructure elements were firstly considered and then the specific risk factors were assigned to the respective element and general risk factor. The 10 **infrastructure elements** that are included are as follows:

- Exposure.
- Road type.
- Road surface.
- Road environment.
- Presence of work zones.
- Alignment - Road segments.
- Cross-section - Road segments.
- Traffic control - Road segments.
- Alignment - Junctions.
- Traffic control - Junctions.

Table 2: Taxonomy of road infrastructure risks related to exposure.

Infrastructure element	General risk factor	Specific risk factor
Exposure	**Traffic flow**	Effect of traffic volume on road safety
		Congestion as a risk factor
		Occurrence of secondary crashes
		Risks associated with varying traffic composition (share of pedestrians, cyclists, PTW, HGV)
		Risks associated with the distribution of flow over arms at junctions

Table 3: Taxonomy of road infrastructure risks related to road type, road surface and road environment.

Infrastructure element	General risk factor	Specific risk factor
Road type	**Road type**	Risks associated with road types
Road surface	**Road surface deficiencies**	Inadequate friction
		Uneven surface
		Ice, snow
		Oil, leaves, etc.
Road environment	**Poor visibility**	Darkness
		Fog
	Adverse weather	Rain
		Snow & frost
		Wind

Table 4: Taxonomy of road infrastructure risks related to work zones.

Infrastructure element	General risk factor	Specific risk factor
Work zones	**Presence of work zones**	work zone length
		work zone duration
		Insufficient signage

Table 5: Taxonomy of road infrastructure risks related to alignment - road segments.

Infrastructure element	General risk factor	Specific risk factor
Alignment - Road segments	**Horizontal / vertical alignment deficiencies**	Alignment deficiencies - Low curve radius
		Alignment deficiencies - Absence of transition curves
		Alignment deficiencies - Frequent curves
		Alignment deficiencies - Densely spaced junctions
		Poor sight distance - horizontal curves
		Alignment deficiencies - High grade
		Alignment deficiencies - Vertical curve radius
		Presence of Tunnel
		Poor sight distance - vertical curves

Table 6: Taxonomy of road infrastructure risks related to cross-section - road segments.

Infrastructure element	General risk factor	Specific risk factor
Cross-section - Road segments	**Super elevation / cross-slopes**	Cross section deficiencies - Superelevation at curve
		Cross section deficiencies - Cross-slope
	Lanes / ramps deficiencies	Cross section deficiencies - Number of lanes
		Cross section deficiencies - Narrow lane
	Median / barrier deficiencies (risk of crash with oncoming traffic)	Undivided road
		Cross section deficiencies - Narrow median
	Shoulder and roadside deficiencies	Shoulder and roadside deficiencies - Absence of shoulder
		Shoulder and roadside deficiencies - Narrow shoulder
		Shoulder and roadside deficiencies - Absence of guardrails or crash cushions
		Shoulder and roadside deficiencies - Absence of clear-zone

		Shoulder and roadside deficiencies - Roadside obstacles (per type of obstacle e.g. trees)
		Shoulder and roadside deficiencies - Risks associated with Safety Barriers and Obstacles

Table 7: Taxonomy of road infrastructure risks related to traffic control - road segments.

Infrastructure element	General risk factor	Specific risk factor
Traffic control - Road segments	**Poor road readability**	Absence of traffic signs
		Misleading or unreadable traffic signs
		Absence of road markings
		Absence of rumble strips

Table 8: Taxonomy of road infrastructure risks related to alignment - junctions.

Infrastructure element	General risk factor	Specific risk factor
Alignment - Junctions	**Interchange deficiencies**	ramp capacity
		ramp length
		acceleration / deceleration lane length
		Absence of channelisation
		Absence of access control
		Poor sight distance
	At-grade junctions deficiencies	High number of conflict points
		Type of junction
		Skewness / junction angle
		Poor sight distance
		Gradient

Table 9: Taxonomy of road infrastructure risks related to traffic control - junctions.

Infrastructure element	General risk factor	Specific risk factor
Traffic control - Junctions	**Rail-road crossings**	Uncontrolled rail-road crossing
	Poor junction readability	Uncontrolled junction
		Misleading or unreadable traffic sign
		Absence of road markings
		Absence of marked crosswalks

2.4 IDENTIFICATION OF HOT TOPICS / STAKEHOLDER CONSULTATION

The **cooperation and interaction with a large group of stakeholders** was crucial for the smoothness and efficiency of each step of the project. The SafetyCube project had already identified a core group of stakeholders from within government, industry, research, and consumer organisations covering the three road safety pillars of a Safe Systems Approach: vehicle, infrastructure, road user. The future users of the ultimate product of the project (the DSS) include Public Authorities (local, regional, national, European and international level), Industry (Infrastructure, Vehicle, Insurance, Technology), Research Institutes, Non-Governmental Organisations, and Mass media.

In order to identify user needs and prioritise risk factors (i.e. identify "hot topics"), 3 workshops were carried out. The first two workshops were of a more general scope, whereas the 3rd one was dedicated to infrastructure issues. The **first workshop** on June 17th 2015 was carried out in Brussels in order to start a dialogue between the project participants and a number of key stakeholders for road safety in Europe. The workshop both introduced the audience to the SafetyCube project and also solicited input from the stakeholders. An extensive list of "hot topics" was also created on the basis of feedback from stakeholders, allowing enhancement of the SafetyCube initial lists. The stakeholders who attended the workshop cover a wide range of interests and knowledge.

To achieve the goal of identifying "hot topics", two activities were undertaken: two breakout sessions and a "hot topic" collection. The collection of "hot topics" was an ongoing activity during the day. The outcome of the "hot topics" exercise covered a wide range of subjects. For instance, there is an interest for the sharing of road environment between bicyclists, e-bikes, the elderly, and other traffic both in shared space 30 km/h zones, crossings, and roundabouts. In the category "Infrastructure", speed limits on highways in different countries and dynamic speed limits were deemed important topics as well as road lighting, self-explaining roads, and forgiving roads.

A **second workshop** was organised in October 2015 in Ljubljana, Slovenia. The first part of the workshop was a plenary session with around 150 participants from the Slovenian Road Safety Councils and IRTAD group representatives. The SafetyCube project was presented as well as the "hot topics" from the previous workshop, all participants were asked to give their feedback on the "hot topics". Feedback was collected both in spoken and written form. The second part of the workshop was a breakout session continuing with participants from the IRTAD group. Thereafter the participants were asked to add, comment and prioritise the "hot topics". This was done on 6 posters showing the "hot topics" from the previous stakeholder consultation.

A **workshop dedicated to road infrastructure** was carried out in February 2016, in Brussels, where 12 road infrastructure stakeholders participated. The participants represented key road infrastructure stakeholders, including EC-INEA, EC-DG-MOVE, EURORAP, ASECAP, ETSC, POLIS network, FIA, BRRC and Belgian regional road authorities. The objectives of the workshop were the analysis of infrastructure stakeholder's needs for the DSS, as well as ranking the infrastructure related "hot topics" in terms of their importance. More specifically, the complete list of "hot topics" identified through the first consultations was examined and ranked in this workshop dedicated to infrastructure.

Both the four general areas and the specific topics within each area were ranked. The four main areas are ranked as follows:

1. **Urban road safety measures** and **Self-explaining and forgiving roads** (which received equal ranks),
2. **Road safety management**,
3. **ITS applications**.

The top ranked specific infrastructure topics as rated by the infrastructure stakeholders for each area are shown in **Table 10**. The SafetyCube analyses will take this ranking into account and put special emphasis on the highest priority topics. It is noted that some of the "hot topics" cannot be addressed from an infrastructure risk factor point of view, as some are clearly related to measures and/or interventions (e.g. road safety management, ITS applications), while others were accounted for during the finalisation of the taxonomy and the related risk factors (e.g. self-explaining roads).

Table 10: Ranking of "hot topics" by road infrastructure stakeholders.

1.Urban road safety (detailed ranking was not possible)	2. Self-explaining and forgiving roads	3. Road safety management	4. ITS application
1. Pedestrians / cyclists	1. Removing obstacles	1. Quality of measures implementation	1. ISA
2. Upgrade of Crossings	2. Introduce shoulder	2. Appropriate speed limits	2. Dynamic speed warning
3. New crossings	3. Alignment (horizontal / vertical)	3. Enforcement	3. ADAS and active safety with V2I
4. Junctions / roundabouts treatments for VRU	4.Sight distance	4. Availability of cost-effectiveness data	4. Implementation of VMS
5. Visibility	5. Traffic signs	5. Work zones	
	6. Raised crossings / intersections		

3 Methodology for evaluating Infrastructure related Risk Factors

This chapter provides an overview of the methodology developed in order to evaluate the scientific literature related to infrastructure risk factors.

The aim was to collect information for each risk factor in as uniform a manner as possible. Therefore a standard methodology was developed within the methodology Work Package of the SafetyCube project (WP3). This included developing a:

- **Literature search strategy,**
- **'Coding template' to record key data and metadata from individual studies,**
- **Guidelines for summarising the findings per risk factor.**

Collating information from a variety of studies each of which may use different underlying theories, designs and methods represented a big challenge. Therefore the approach and 'coding template' developed was designed to be flexible enough to capture important information but also facilitate the comparison between studies. These documents and the associated instructions and guidelines can be found in Martensen et al (2017).

3.1 STUDY SELECTION (OVERALL APPROACH)

3.1.1 Literature Search

For each of the identified risk factor topics **a standardised literature search** was conducted in order to identify relevant studies to include in the Decision Support System (DSS) and to form a basis for a concluding summary (synopsis) and further analyses. A standardised procedure was developed (D3.4) and applied for each examined risk factor in this report. It should be noted that the literature search process was started for each risk factor in the taxonomy, however, in some cases insufficient literature was identified and some risk factors could not be evaluated.. The literature searches were carried out between May and September 2016. The literature search, study coding and synopses creation for a particular risk factor was completed within the same SafetyCube partner organisation. The process was documented in a standard format to make the gradual reduction of relevant studies transparent. This documentation of each search is included in the corresponding supporting documents of the synopses (see Appendix).

The **main databases used** in WP5 are the following:

- Scopus
- TRID

or some risk factors the following **additional databases** were used

- Google Scholar
- Science Direct
- Taylor & Francis Online
- Springer Link

3.1.2 Prioritising studies to be coded

The aim was to find studies that provided an estimate of the risk of being in a crash due to the presence of the risk factor. Therefore, **studies considering crash data were designated the most**

important. However, while the actual occurrence of crashes can be seen as the ultimate outcome measure for road safety, Safety Performance Indicators (SPI) have in recent years been taken into consideration to quantify the road safety level (Gitelman et al., 2014). SPIs include driving behaviour, like speed choice and lane positioning. These metrics give an indication of safe (or unsafe) driving behaviour. The SPI variables included for analysis are those for which there is some scientific evidence of an association with increased crash risk. For some risk factors, studies considering SPIs are included in addition to those focusing directly on crashes. However, where possible the coding of studies including crash data was prioritised.

Since the study design and the outcome variables are just basic criteria, for some risk factors the literature search had the potential to yield an excessive number of related studies and therefore additional selection criteria were adopted. Furthermore, on major and well-studied infrastructure risk factors, meta-analyses were available and the results of these were identified and incorporated. While the aim was to include as many studies as possible for as many risk factors as possible, it was simply not feasible, given the scope and resources of the project, to examine all available studies for all risk factors and their variants. The general **criteria for prioritising studies to be selected for further analysis and eventual inclusion in the DSS** were based on the following guideline:

- Key meta-analyses (studies already included in the key meta-analysis were not coded again)
- Most recent studies
- High quality of studies
- Country origin: Europe before North America/Australasia before other countries
- Importance: number of citations
- Language: English
- Peer reviewed journals

According to the level of detail of the topic and the history of research in the field, the exact approach to prioritisation and number of studies that were eligible for 'coding' varied (see synopses for the number of studies included per topic).

A challenge within the task of identifying studies to be included in the repository of risk factor studies was **to distinguish between risk factors and countermeasures**. For example, studies dealing with the absence of a safety barrier may be designed to record e.g. crashes before and after the installation of a safety barrier. Although dealing with a risk factor, these studies describe effects resulting from the treatment of a risk factor/application of a remedial measure. Such studies will be coded and considered within the measures analysis of future deliverables (WP5.2). This report (Deliverable 5.1) discusses results related to risk factors only.

3.2 STUDY CODING

Within the aim of creating a data-base of crash risk estimates related to road infrastructure design and layout, **a template was developed within WP3** to capture relevant information from each study in a manner that this information could be uniformly reported and shared across topics and WPs within the overall SafetyCube project. Guidelines were also made available for the task of coding with detailed instructions on how to use the template. The coding template was designed to accommodate the variety and complexity of different study designs. At the same time its complexity required partners to learn how to use it.

For each study the following information was coded in the template and will ultimately be presented in the DSS:

- Road system element (Road User, Infrastructure, Vehicle) and level of taxonomy so that users of the DSS will be able to find information on topics they are interested in.

- Basic information of the study (title, author, year, source, origin, abstract
- Road user group examined
- Study design
- Measures of exposure to the risk factor
- Measures of outcome (e.g. number of injury crashes)
- Type of effects (within SafetyCube this refers to the numerical and statistical details of a given study in a manner to quantify a particular association between exposure (either to a risk factor or a countermeasure) and a road safety outcome)
- Effects (including corresponding measures e.g. confidence intervals)
- Limitations
- Summary of the information relevant to SafetyCube (this may be different from the original study abstract).

For the full list of information provided per study see Martensen et al (2017). **Completed coding files (one per study) were uploaded to the DSS relational database**. In total, more than 270 studies on infrastructure related risk factors have been coded within WP5.

3.2.1 Quality control for coding task

Even though the instructions for coding were detailed, these still allowed room for interpretation e.g. which design describes the study the best (if not mentioned by author), which estimates to include or exclude, what are essentially the weak points of the study etc. Therefore, **a quality control procedure was established** in which all risk factors were allocated to the primary and secondary coding partner. The primary coding partner undertook the literature search, selected the papers for coding and coded these studies. The initial coded studies for each partner where shared between primary and secondary coding partners to confirm coding decisions. Once there was agreement on the coding of the initial studies, the rest of the studies were coded without sharing between the primary and secondary coding partners unless the studies were complicated or caused problems for the coders. These complicated studies which proved were discussed between the primary and secondary coding partner so as to reach consensus. Coders had the opportunity to have more than one study checked if they were uncertain.

3.3 SYNOPSES CREATION

The DSS will provide information for all coded studies (see above) for various risk factors and measures. The synthesis of these studies will be made available in the form of a 'synopsis' indicating the main findings for a particular risk factor derived from **meta-analyses or another type of comprehensive synthesis of the results** (e.g. vote-count analysis), according to the guidelines and templates available in Martensen et al. (2016).

In WP5.1, synopses were created for several risk factors on different levels of the risk factor taxonomy, thus, for different levels of detail, mainly dependent on the availability of studies for a certain topic. The synopses contain context information for each risk factor from literature that could not be coded (e.g. literature reviews or qualitative studies). However, not all the coded studies that will populate the DSS are included in the analysis of the synopsis. For some risk factors where it was possible to code only a few studies, these coded studies will be included in the DSS. However, there was not enough information to write a full synopsis.

The synopses aim to facilitate different end users: decision-makers looking for global estimates vs. scientific users interested in result and methodological details. Therefore, they contain sections for different end user groups that can be read independently. The **structure of each risk factor**

synopsis, including the corresponding sub items (uniform for human, vehicle, and infrastructure related risk factors), is as follows (note. Slight differences occur between synopses due to the variability in information from the literature) :

1. **Summary**
   i. Abstract
   ii. Overview of effects
   iii. Analysis methods
2. **Scientific overview**
   iv. Short synthesis of the literature
   v. Overview of the available studies
   vi. Description of the analysis methods
   vii. Analysis of the effects: meta-analysis, other type of comprehensive synthesis like vote-count table or review-type analysis
3. **Supporting documents**
   viii. Details of literature search
   ix. Comparison of available studies in detail (optional)

3.4 INFRASTRUCTURE-RELATED CRASH SCENARIOS USING IN-DEPTH AND MACROSCOPIC CRASH DATA

To enrich the background information in the risk factor synopsis, **in-depth accident data** from the German In-Depth Accident Study (GIDAS) and overview data from the CARE CADaS database was analysed[2]. There, where these data sources describe the relationships between an infrastructure risk factor and crashes, the related data has been included in that specific synopsis. Risk factors that were dealt with in the databases include **type of road, section of road (straight, junction etc) and crash type**. In these cases a radarplot is included in the synopsis to present the findings. In should be noted that the CARE data presents a summary situation for all EU member states (or as many as report figures for a particular risk factor). In contrast the GIDAS data is for Germany only. This may not be representative of other EU countries. The crash data provided in synopses are intended to serve only as an indication of the situation for the risk factor.

As an example, Figure 55 gives an overview of the distribution of crash locations for the percentage of crashes which occurred during congestion per road type. It is clear that the risk factor of congestion has a distinctive "footprint" with a greater percentage of accidents taking place on motorways, while country roads are underrepresented. However, this picture may be due to the lack of data on the length of different road types in that country, as well as the frequency of congestion in these different road types (i.e. motorways may be more often congested than country roads).

[2] French in-depth data (LAB database) data were also provided and examined but eventually not used in the synopses, mostly due to low number of cases for the risk factors concerned.

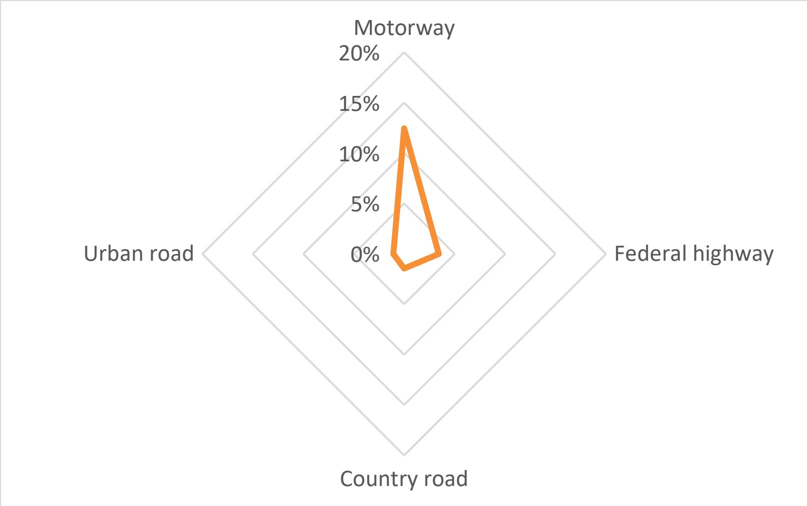


Figure 5: Radar plot of percentage of crashes that occurred in congestion per road type from the GIDAS (German) database.

3.4.1 In-depth accident database GIDAS

Crash scenario analysis conducted using cases from the German In-Depth Accident Study (GIDAS) database considers all accidents which were ready for analysis and which were collected in the years 2007 to 2015. In total, records from 14, 398 accidents which occurred in the regions of Hannover and Dresden were analysed. The GIDAS database details those accidents which occurred on a public road where at least one person was injured. The accidents are collected according to a statistical sampling process to ensure a high level of representativeness of the actual accident situation in the sample regions. The data collection is conducted using the "on the scene" approach where all factors which were present at a crash are recorded. This does not mean that the recorded factor was a contributory factor towards the crash. Note that, the risk factor is identified in relation to the involved party who was considered most at fault

The German In-Depth Accident Study (GIDAS) is a joint venture between Federal Highway Research Institute (BASt) and the German Association for Research in Automobile Technology (FAT), initiated in July 1999. It is the largest in-depth accident study project in Germany and based on the work of the BASt-founded investigation team at the Hanover Medical School (MHH), in co-operation with the investigation team of the Technical University Dresden. Approximately 2,000 accidents involving personal injury are recorded in the area of Dresden and Hannover annually (Otte et al., 2003).

In GIDAS, road traffic accidents involving personal injury are investigated using the "on the scene" approach and are collected according to a statistical sampling process. This means that teams are called promptly after the occurrence of any kind of road traffic accidents with at least one injured person which occurred in determined time shifts. Comparisons with the official accident statistics are made regularly and weighing factors are applied (to avoid biases). Investigation areas were chosen accordingly to represent the German national road network and built-up areas.

The detailed documentation of the accidents is performed by survey teams consisting of specially trained students, technical and medical staff. The documentation scope obtained reaches up to 3,000 encoded parameters per accident. The data scope includes technical vehicle data, crash information, road design, active and passive safety systems, accident scene details, and cause of the accident. Surveyed factors include impact contact points of passengers or vulnerable road users, environmental conditions, information on traffic control, and other parties (road users) involved. To collect detailed injury and accident causation information individual interviews of the involved accident participants are followed by detailed surveying of the accident scene based on existing evidence. All information available retrospectively is collected in close collaboration with police, hospitals and rescue services and each documented accident is reconstructed in a simulation program (entire course of the accident).

3.4.2 CARE Accident database

Crash scenario analysis conducted using cases from the CARE Database, considers all fatal accidents[3] recorded in year 2013. In total, records from 23 577 accidents which occurred in 28 European countries were analysed. CARE Database comprises detailed data on individual accidents as collected by the Member States. Data are recorded according to a Common Accident Data Set (CADaS) consisting of a minimum set of standardised data elements, which allows for comparable road accident data to be available in Europe. Accident reports note all factors which were present at a crash. This does not mean that the noted factor was a contributory factor towards the crash. Note that, the risk factor is identified in relation to the involved party who was considered most at fault.

3.5 FINAL SYNOPSES

The full taxonomy of infrastructure risk factors can be found in Chapter 2.2. In applying the method outlined in this chapter it was initially intended that each of the 59 specific risk factor would have a synopsis. However, following completion of the search and coding procedure it became apparent that **for some specific risk factors there were insufficient code-able studies to justify the preparation of a synopsis**.

For the following infrastructure risk factors it was not possible to produce synopsis for each specific risk factor:

- Road Surface (Road type, road surface and road environment): One synopsis for road surface was produced at the risk factor level, rather than for each specific risk factor.
- Insufficient signage (Workzone): The synopsis for insufficient signage could not be completed due to insufficient identified studies.
- Vertical curve radius (Alignment - road segments): The synopsis for vertical curve radius could not be completed due to insufficient identified studies.
- Poor sight distance – Horizontal curves and Vertical curves (Alignment - road segments): The synopses for poor sight distance – horizontal and vertical curves could not be completed due to insufficient identified studies.
- Cross-slope (Cross-section - road segments): The synopsis for cross-slope could not be completed due to insufficient identified studies.
- Guardrails, crash zone and roadside obstacles (Cross-section - road segments): One synopsis was developed covering absence of guardrails, crash zone and roadside obstacles.
- Traffic control - road segments, Poor road readability: no synopsis were produced for any specific risk factors because of the difficulty separating risks from measures. This topic will be considered when measures are evaluated in Deliverable 5.2.
- Absence of channelization (Alignment – junctions): The synopses for absence of channelization could not be completed due to insufficient identified studies.

[3] Data refer to those accidents where at least a person was fatally injured (death within 30 days of the road accident, confirmed suicide and natural death are not included).

- Absence of access control (Alignment – junctions): The synopses for absence of access control could not be completed due to insufficient identified studies.
- Misleading or unreadable traffic sign (Traffic control – junctions): The synopsis for misleading or unreadable traffic sign could not be completed due to insufficient identified studies.
- Absence of road markings and absence of marked crosswalks (Traffic control – junctions): One synopsis was developed covering both absence of road markings and absence of marked crosswalks.

Ultimately 37 synopses on road infrastructure risks have been developed for inclusion in the DSS. This has been completed by 9 different SafetyCube partner organisations.

4 Risk factor analysis

This chapter provides an overview of all infrastructure related risk factor synopses that have been written as of October 2016 and these will be available through the DSS when it is launched in 2017. However, since these are very comprehensive documents, only the abstracts and the corresponding colour code - which indicates the level of evidence for a given risk factor will be provided in this chapter. The synopses are intended to be periodically updated to reflect new research or in some cases to expand their scope. The full text of the synopses in their current form can be found in Appendix A and any future updates or additions will be available on the project website (http://www.safetycube-project.eu/) and the DSS.

The colour code indicates how important this risk factor is in terms of the amount of evidence demonstrating its impact on road safety as regards increasing crash risk, frequency or severity. The following codes and definition were applied:

- **Red: Risky**. Consistent results showing an increased risk of crashes or injuries when exposed to this risk factor.
- **Yellow: Probably risky**. Some evidence that there is increased risk when exposed to this risk factor, but results are not consistent. This could be because while the majority of studies demonstrate a risk, there may be some studies with inconsistent results. Or, studies indicate a risk but are few in number or have methodological weakness.
- **Grey: Unclear**. Studies report opposite effects. There are few studies with inconsistent results, few studies with weak indication or risk.
- **Green. Probably not risky**. Studies consistently demonstrate that this risk factor is not associated with increased crash risk, frequency or severity.

Following the colour code an **abstract** is provided for each risk factor. This provides an overview of the main text in the summary and scientific overview of the synopsis. In the following sections, the colour codes and abstracts are provided for the specific risk factors under each of the 10 infrastructure elements, namely;

- Exposure.
- Road type.
- Road surface.
- Road environment.
- Presence of work zones.
- Alignment - Road segments.
- Cross-section - Road segments.
- Traffic control - Road segments.
- Alignment - Junctions.
- Traffic control - Junctions

4.1 EXPOSURE

4.1.1 Effect of traffic volume on road safety

Full risk factor evaluation can be found in Appendix A.1.

Colour code: Red

Most of the reviewed studies find higher traffic volumes to be associated with a net increase in crashes, but a crash increase less than proportional to traffic volume increases, indicating a lower risk for each road user. However, the effect of traffic volume on crash occurrence appears to differ between crash types (e.g. single-vehicle and multi-vehicle crashes).

Abstract

Traffic volume, or traffic flow, denotes the number of vehicles passing a given point or section of a road for a given time unit. The relationship between accidents and traffic volume appears to be non-linear. Most reviewed studies find that higher traffic volumes are associated with a net increase of crashes. The number of crashes increases less than proportionally to traffic volume. This indicates that an increase in traffic volume is associated with a lower risk for each road user (since risk = crashes/exposure). Several studies find that the effect of traffic volume on crash occurrence differs between crash types. For multi-vehicle crashes, most studies indicate that both the frequency and the risk of such crashes increase at higher traffic volumes. While it seems clear that traffic volume is related to crash occurrence, the form of this relationship (which might differ for different crash types), and the mechanism explaining these relationships remain somewhat unclear. It is also not clear how traffic volume affects road safety on different road types.

4.1.2 Congestion as a risk factor

Full risk factor evaluation can be found in Appendix A.2.

Colour code: Grey

Studies on congestion find mixed results on how this affects road safety. The effects might differ based on the crash types and/or congestion indicators considered.

Abstract

Congestion refers to a traffic state with slow-moving or still-standing traffic, which could occur due to road, traffic, or weather situations. Congestion might affect road safety due to decreased speed (less severe crashes), high degrees of speed variation within and between lanes increasing the complexity of driving (more crashes), or by creating stress (detrimental for driver behaviour). Most studies define congestion based on travel time, speed, or traffic density. Studies using a density-based definition of congestion (volume/capacity-ratio) report congestion to be associated with fewer crashes in total, but find different tendencies for single-vehicle and multi-vehicle crashes. Studies defining congestion by increased travel time or decreased speed generally find congestion to be associated with a higher number of crashes (including injury crashes), but this is not reported under all conditions. Due to a low number of relatively dissimilar studies, the effect and potential transferability is uncertain. Most reviewed studies are from the United States, and all are based on motorways, which could explain the somewhat surprising result that injury accidents are not found to decrease in congested traffic states. No distinctions are made between different road users.

4.1.3 Occurrence of Secondary crashes

Full risk factor evaluation can be found in Appendix A.3.

Colour code: Yellow

The presence of a crash or an incident can contribute to the occurrence of additional (secondary) incidents or crashes. The prevalence of secondary crashes, and the factors contributing to their occurrence is unclear, as this varies between studies.

Abstract

The occurrence of an initial crash or incident (e.g. vehicle breakdown) may increase the risk of secondary crashes and incidents occurring, by causing (non-recurrent) congestion, traffic flow disruption and/or driver distraction. Studies find that 0.4 to 8.4 % of crashes on motorways are secondary, i.e. caused at least in part by a prior crash or incident. Most secondary crashes occur in the same direction and upstream of a prior crash, and a longer duration of the prior crash/incident is associated with greater risk of secondary crash occurrence. The methodology applied for classifying crashes as secondary varies greatly among studies, but is generally based on estimates of the queue caused by the prior crash/incident. The available literature has not investigated the extent of secondary crashes on roads other than motorways, nor the risk for different transportation modes.

4.1.4 Risks associated with varying traffic composition

Full risk factor evaluation can be found in Appendix A.4.

Colour code: Red

As the share of cyclists and/or pedestrians in the traffic flow increases, an increase in the number of crashes is less than would be expected for the proportional increase in traffic volume, indicating a lower risk for each road user at higher volumes. The effect of the share of HGVs on road safety is unclear.

Abstract

Traffic composition refers to the share of different groups of road users in traffic (e.g. cars, pedestrians, cyclists, Heavy Goods Vehicle (HGV)s, Powered Two Wheelers). An increase in the volume of cyclists and pedestrians is associated with a net increase in crashes (between cyclists/ pedestrians and motor vehicles), but this increase is less than would be expected for the proportional increase in volume, corresponding to lower risk for each road user: A meta-analysis estimated that a doubling of the volumes of pedestrians or cyclists would correspond to a 41 % increase in crashes (across road types and areas). This is in accordance with a Safety-in-Numbers effect (more cyclists/ pedestrian corresponds to a lower crash risk for each cyclist/pedestrian), but it remains unclear if the lower risk is caused by the higher numbers of pedestrians/cyclists. The effect of the share of heavy goods vehicles on road safety is unclear (few studies with mixed results), and no studies were found on the share of PTWs or public transport.

4.1.5 Risks associated with the distribution of traffic flow over arms at junctions

Full risk factor evaluation can be found in Appendix A.5.

Colour code: Grey

There was adequate number of studies investigating the risk factor of distribution of traffic flow over arms at junctions, but distribution of flow over arms at junctions was rarely the main variable of interest included in the crash models. Furthermore, the risk factor is not expressed in a consistent way across the studies, resulting in an unclear picture of its overall effect.

Abstract

In the case where primary and secondary roads converge, the distribution of traffic flow over the arms of a junction can introduce a non-trivial risk. In general, it is not easy to make a clear conclusion

about the effect of the distribution of traffic flow over the arms of a junction. This is due to the different variables that the different studies used to express the specific risk factor. In situations where there is an increase to (i) the traffic on the minor or major road, (ii) the ratio of major road traffic to the minor road traffic, or (iii) the number of turn lanes, crash frequency tends to increase. On the contrary, when there is a high flow imbalance between the junction branches, the number of crashes reduces. Crash severity also increases with an increase in the major road's Annual Average Daily Traffic (AADT). Finally, the SafetyCube meta-analysis showed that the amount of traffic flow of the secondary road of a junction can result in an increase in the number of crashes at a 95% confidence level.

4.2 ROAD TYPE, ROAD SURFACE AND ROAD ENVIRONMENT

4.2.1 Risk of Different Road Types

Full risk factor evaluation can be found in Appendix A.6.

Colour code: Yellow

International literature indicates that, when all road users are considered together, the "higher" the road type/class is, greater the accident and injury rate will be and the higher the risk of severe injuries will be. However, not all literature highlighted statistically significant results and road type/class categories used in the studies varied, so had to be grouped in the overall analysis (e.g. motorways grouped with other major arterial roads), leading to potentially over-generalised results.

Abstract

For most countries, road are generally organised into classes which reflect the main function and traffic type they are designed for, and this is described as road functional class, or in general, road type. In the literature analysed, all road types were considered, from minor local roads to major arterial roads and motorways, but the categorisation used varied across each country and study, which made road type a complicated topic to analyse. Studies used either accident rate, casualty rate or injury severity as a measure of the risk of road types. It was found that overall, minor roads were statistically significantly safer than major roads in terms of both accident and casualty frequency and also injury severity. This result was reversed when examining particular cases (e.g. collisions only involving tractor-trailers). However, not all studies were statistically significant and the overall results may be generalised due to having to group road type categories across studies to allow a cross-study analysis to be made.

4.2.2 Road Surface Deficiencies - Inadequate Friction

Full risk factor evaluation can be found in Appendix A.7.

Colour code: Red

There is a strong statistical relationship between road surface condition and road safety outcomes. The most significant impact can be attributed to the friction. Improving road surface friction reduces the number of crashes. The effects are greatest on wet roads, and when friction initially is low. Friction seems to be more important for accident rates than other road surface deficiencies e.g. unevenness. Studies have also shown that ruts (sunken tracks made by the passage of vehicles) have a rather insignificant impact on road safety. On dry roads, ruts improve road safety by slowing traffic speed; however, on wet roads ruts create risk of aquaplaning. Unevenness, in comparison with ruts, has a more significant and negative impact on road safety.

Abstract

Road surface or pavement is the durable surface material laid down on an area, intended to sustain vehicular or foot traffic. Our focus was on primarily surfaced rural roads and not gravel roads. The most commonly used material is asphalt. Skid resistance is one of the most important surface properties with regard to safety, directly related to friction adequacy; it decreases continuously with time, due to the polishing action of the traffic. The road conditions are also distinguished by adhesion coefficient; good adhesion coefficient plays a decisive role in preventing a rear-end collision. Several studies have shown that there is a significant correlation between accident risk due to skidding and the pavement's skid resistance. Improving road surface friction reduces the number of accidents. The effects are greatest on wet roads, in sharp bends and when friction is initially low. Poor pavement conditions at low-speed roads result in less severe crashes for single-vehicle collisions but more severe crashes for multi-vehicle collisions. In the case of single-vehicle collisions at low-speed and multi-vehicle collisions at medium- and high-speed, higher severity levels are observed when pavement conditions are poor.

4.2.3 Adverse weather conditions – Rain

Full risk factor evaluation can be found in Appendix A.8.

Colour code: Yellow

Rain has been consistently shown to be a risk factor in the sense that the crash rate (the number of crashes per vehicle or km-driven) is higher in the rain than in comparable situations without rain. This has however, mainly been tested with motor vehicles, and it is not clear whether it is true for other road users as well.

Abstract

Rain has been consistently shown to be a risk factor (in Europe) in the sense that the injury crash rate (the number of accidents per vehicle or km-driven) is higher in the rain than in comparable situations without rain. This has however, mainly been tested with motor vehicles, and it is not clear whether it is true for other road users as well. The effect on fatal or severe crashes is less reliable and crashes in rainy conditions have been found to be less severe (except in Scandinavian countries).

The net-effect on crash occurrence can differ substantially from the risk effect of rain, because adverse weather conditions also affect the mobility, in particular for vulnerable road users who are more exposed to the weather. Consequently the net effect of crash occurrence yields much more mixed results with decreases in crash numbers observed more often for vulnerable road users and in urban areas. More research is needed to disentangle risk-effects and mobility-effects for vulnerable road users.

4.2.4 Adverse weather conditions – Frost & Snow

Full risk factor evaluation can be found in Appendix A.9.

Colour code: Grey

Frost and snow are more often found to reduce crashes than to increase them. However, frost and snow also lead to a reduction in traffic participation – in particular for unprotected road users like cyclists, pedestrians and motorcyclists. So far, these mobility effects have been insufficiently accounted for, leaving the true risk unknown.

Abstract

The effects of snow and frost on accident occurrence and risk have been found to be very inconsistent. For frost, if results are significant, they indicate a reduced crash occurrence (i.e. an improvement of road safety). Only on motorways frost tends to lead to an increased crash risk. For snow the results are more inconsistent with somewhat more positive effects (i.e. reduction of accidents) than negative effects (increased accident numbers). The first snow after a time of no snow seems to be consistently associated with a higher crash risk.

The risks associated with frost and snow are slippery roads and for snow also reduced visibility. These risks might be offset by more careful road user behaviour. However, much more likely the actual crash risk is influenced by a reduction of mobility (traffic volume) – in particular for unprotected road users like pedestrians, cyclists, and motorcyclists. So far, these mobility effects have been insufficiently accounted for, leaving the true risk unknown.

4.2.5 Poor visibility-Darkness

Full risk factor evaluation can be found in Appendix A.10.

Colour code: Yellow

Darkness has been consistently shown to be associated with an increase of crash risk for pedestrians. An overall increase in risk for all road users has been found in most studies, however, this overall effect seems to be predominantly carried by an increased risk for pedestrians, and possibly for two-wheelers. Darkness is also associated with an increased severity of crash in the sense that severe and fatal crashes increase while crashes with minor injuries decrease in darkness.

Abstract

When considering the total number of crashes, the absence of light is associated with an increased risk of crash. This effect is confirmed for pedestrians for which the crash risk is systematically higher in darkness than in daylight. The crash risk for pedestrian is estimated to be 2 to 4 times higher in such conditions. The risk of crash in darkness also seems to increase for powered two-wheelers, but to a lesser extent (relative risk below 2). For cars, results do not show any significant impact of darkness. As fatalities and serious injuries are more likely in darkness than in daylight, while for slight injury crashes it is the other way round, it can be concluded that darkness crashes show and increased severity

4.3 PRESENCE OF WORKZONES

4.3.1 Workzone Length

Full risk factor evaluation can be found in Appendix A.11.

Colour code: Red

The presence of long workzones is intuitively considered as a risk factor, since more crashes are likely to occur in extensive work zone areas (increased crash risk). This result was reported by all coded studies, which have shown a consistent negative effect on the number of crashes (increased crash risk) and was also confirmed by the meta-analysis carried out. One study also indicates that increased lengths of work zones increase the probability of crash occurrence.

Abstract

It can be assumed that long work zones may increase risk of crashes, because work zones are unfamiliar road environments for most road users, due to special arrangements (lane closures, traffic disruptions, changes in road delineation and signage, presence of barriers, obstacles, workers etc.). In general, work zone length was found to significantly increase the number of crashes. The vast majority of international literature investigates crash frequency, indicating that longer work zone lengths in road networks are associated with an increased number of crashes at a 95% confidence level. This result is confirmed by the meta-analysis that was carried out, which revealed a significant overall estimate of work zone length. Moreover, only one study that investigates crash risk (probability of crash occurrence vs non-crash occurrence) was found, suggesting that work zone length significantly increases crash risk.

4.3.2 Workzone Duration

Full risk factor evaluation can be found in Appendix A.12.

Colour code: Grey

The presence of long duration of workzones was initially considered a risk factor as longer workzones are associated with more crashes. This was reported by almost all coded studies which show a consistent increase in the number of crashes and confirmed by the preliminary (uncorrected for publication bias) meta-analysis carried out. However, publication bias was detected and the corrected meta-analysis showed a non-significant effect.

Abstract

Presence of long duration work zones can cause safety issues to drivers, because work zones are unfamiliar road environments for most road users, due to special arrangements. In general, however, work zone duration was found to have a non-significant impact on road safety. The vast majority of international literature investigates crash frequency, indicating that increased duration of works in road networks leads to an increased number of crashes at a 95% confidence level. However, the meta-analysis carried out, revealed a non-significant overall estimate of work zone duration after correcting for publication bias. Moreover, only one study was found to investigate crash risk (probability of crash occurrence vs non-crash occurrence), suggesting that work zone duration has no significant effect on crash risk.

4.4 ALIGNMENT - ROAD SEGMENTS

4.4.1 Alignment deficiencies-Low curve radius

Full risk factor evaluation can be found in Appendix A.13.

Colour code: Red

Curve radius is a crash risk factor since there is a direct relationship between the radius of a horizontal curve and crashes and crash outcomes. The smaller the curve radius, the larger the risk for crashes. The radius of curve interacts with other design elements (horizontal alignment, vertical alignment, superelevation, side friction) to enable safe driving in the curve.

Abstract

Average crash rates are higher on horizontal curves than on straight sections of rural 2-lane highways. Radius or degree of curvature consistently tops the list of geometry variables that most significantly affect operating speeds and crash experience on horizontal curves. The crash rate increases with lower curve radii (tighter curves), with strong increase for radii < 200 metres. In general sharp curves in combination with long straight sections, sharp vertical sag or sharp crest curves, and a sequence of gentler curves are factors that increase risk in curves. For specific groups of drivers, such as motorcyclists and truck drivers, curves with low radii may be more risky than for other drivers and may require additional risk mitigating measures. The analysis of coded studies confirmed that curves with low radii have a higher crash risk. Moreover this analysis showed that crash modification functions for curve radius are very different for curve radii < 200 metres, with particular steep functions for Germany and USA. Based on USA rural highway studies, the analysis of coded studies found steeper crash modification factors for fatal/injury crashes than for Property Damage Only (PDO) crashes; it was also found that low curve radius is especially risky in interaction with vertical sag or crest curves, and that curve radius was the strongest predictor for motorcycle-to-barrier crashes.

4.4.2 Alignment deficiencies - Absence of transition curves

Full risk factor evaluation can be found in Appendix A.14.

Colour code: Yellow

Although there may be a significant relationship between absence of transition curve and risk, the relationship is dependent upon various external factors, including type of terrain (level, rolling, mountainous), road width and Average Daily Travel (ADT). Relatively speaking, absence of transition curves is a much smaller risk factor than curve radius.

Abstract

Transition curves are defined as the transition between a tangent and a circular curve. In a transition curve, the curve radius is not constant but gradually changes. These curves are often designed as clothoids (i.e. curves where the radius of curvature decreases linearly as a function of the arc length). Theoretically, a curve transition should improve safety because it gradually leads the driver into a natural safe path on the circular curve and it provides a space for superelevation to gradually change, thus minimizing excess side friction forces. The analysis of coded studies reveals that curved roads with transition curves are associated with improved driving performance and lower crash risk. Studies have shown a significant relationship between the absence of transition curve and risk, but this relationship is dependent upon various external factors including type of terrain (level, rolling, mountainous), road width, and ADT. There is an apparent interaction between the landscape and road design elements in curves and the application of transition curves strengthens these interactions and results in improved safety. However, the influence of transition curves on crashes is far less than the radius of the curve.

4.4.3 Alignment deficiencies - Frequent curves

Full risk factor evaluation can be found in Appendix A.15.

Colour code: Grey

Only three relevant papers were found suitable for coding. All three studies indicate that an increased risk is found for a higher degree of bendiness. However, two of the papers are by the same author and research group. The number of coded papers is insufficient to allow for a meta-analysis and an overall effect is difficult to isolate since the number of papers is too small and the indicator itself does not appear to have a clear causal relation with crashes. Also, the coded studies refer to other studies where no relation or the opposite effect was found.

Abstract

Curves are considered to be a risk factor in the design of roads. Most research on the risk of curves focuses on individual curves, only a few studies focus on the frequency of curves. Findings from those studies are inconsistent. Five studies report a higher risk of crashes on roads with a higher frequency of curves, or found no relation, while three more recent studies report a lower risk on crashes with a higher frequency of curves. Studies reporting lower crash numbers on roads with more curves hypothesise that this might be due to a better anticipation of drivers on curves. Checks

are missing however if the number of curves is related to the amount of traffic or to safety measures on more dangerous curves. The findings on frequent curves are therefore inconclusive.

4.4.4 Alignment deficiencies - Densely spaced junctions

Full risk factor evaluation can be found in Appendix A.16.

Colour code: Grey

Increased junction density can contribute to an increase in crashes, as a result of an increase in the conflict potential. However, research into the effect is inconclusive. The fact that increased junction density increases total crashes but seems to reduce crashes among pedestrians suggests that increased junction density should only be advocated in urban areas where pedestrians are the predominant mode and where motorised traffic is low.

Abstract

Junction density has been identified as a risk factor although the results of research into the effect of junction density on crash frequency and/or crash severity (number and extent of injuries) is inconclusive. Some studies indicate that denser street networks with higher densities of junctions lead to fewer crashes across all severity levels. Other studies reveal the opposite with increases in the density of certain junction types leading to significantly more crashes of a certain type, or of all crashes.

4.4.5 Alignment deficiencies - High Grade

Full risk factor evaluation can be found in Appendix A.17.

Colour code: Yellow

The presence of steep uphill or downhill vertical grades can contribute to the occurrence of accidents, to increased crash severity and injury severities, and incidents of speeding. The exact amount of the effect is unclear, as this varies between studies, with few also bordering on statistical significance.

Abstract

High grades increase or decrease vehicle acceleration and speed, and thus make a vehicle harder to control precisely, especially if it has a lot of inertia and increased handling difficulty, such as heavy goods vehicles (trucks). This especially applies in cases where high grade or grade variations coincide with sharp horizontal curves, which is why a number of studies examine this combination of risk factors. Moreover, it is understood that the presence of grades may influence driver behaviour, inducing additional acceleration or deceleration. The presence of steep uphill or downhill vertical grades in the road geometry, either alone or combined with horizontal curves, affects the level of road safety. This translates not only to induced accidents (both absolute numbers and frequencies), but also to increased injury severity and speeding which has been proven to lead to accidents. A vote-count analysis was performed to capture these overall effects for high grade.

4.4.6 Presence of Tunnels

Full risk factor evaluation can be found in Appendix A.18.

Colour code: Yellow

Explanation: The presence of tunnels can contribute to the occurrence of crashes; it can sometimes increase crash and injury severities, and also influence lateral control. The exact size of the effect is unclear, as this varies between studies, with few also bordering on statistical significance. There have also been some contradictory findings between studies.

Abstract

Tunnels are widely used globally for ease of access and locomotion. However the presence of tunnels in road segments, either alone or combined with horizontal or vertical curves, affects the level of road safety. This translates not only to induced crashes, but also to increased injury severity and changes of the degree of lateral control which could be linked with crashes.

4.5 CROSS-SECTION - ROAD SEGMENTS

4.5.1 Cross-section deficiencies - Superelevation

Full risk factor evaluation can be found in Appendix A.19.

Colour code: Yellow

The coded studies show that an increase in the superelevation relates to a decrease in crashes. Reversely it can be stated that a deficient superelevation relates to an increase in crashes. Although studies used different methodologies and analysed different outcomes, the results were consistent in showing that a superelevation deficiencies (typically defined as difference between the actual and the optimal superelevation) relate to a higher risk on crashes in curves.

Abstract

The superelevation is the right-angled slope of the road surface and is part of the horizontal curve design. Driving through a curve at too high speeds can create too high centrifugal forces causing a vehicle to skid (if the skid resistance is also too low) or to roll over. In combination with other curve design components like the curve radius and pavement friction, the superelevation decreases the risk of skidding or rolling over for vehicles driving through the curve at the design speed. Apart from reducing the risk of skidding or rolling over, the superelevation provides for water runoff. The superelevation can also increase crash risk when it is too high. It can cause vehicles too slide or roll over inwards toward the curve. The risk of such an event increases given the combination of too high superelevation rates, vehicles driving slowly, the road is slippery or on combinations of horizontal curves and vertical grades. Four coded studies all found that superelevation deficiencies relate to an increase in crashes at curves. Passenger vehicles were found to be more prone to skidding than rolling over. Heavy good vehicles on the other hand were found to be prone to rolling over due to a relatively high centre of mass. Also, the studies indicated that taking operational speeds into account in the design and evaluation of curves will result in a more robust curve design.

4.5.2 Cross-section deficiencies - Number of lanes

Full risk factor evaluation can be found in Appendix A.20.

Colour code: Red

Research shows that the number of lanes can contribute to the number of crashes. Regardless of the included covariates and used methods the effect of an increasing number of lanes is in the vast majority of cases negative (an exception for mountainous roads was detected). The effect of number of lanes on crashes depends upon its interaction with other characteristics of the roadway, specifically, lane width and shoulder width.

Abstract

Most of the studies show that an increasing number of lanes is related to an increase in crashes. This might be partly contributed to an increase in lane changing and overtaking manoeuvres and speed differences between vehicles. Another relationship is that a higher number of traffic lanes relates to a higher traffic demand. This means that the relation between number of lanes and crashes is not causal. The effect of the number of lanes on crashes always concerns the number of crashes or total crash reduction, for which often a distinction has been made in crash severities. A distinction between crash types is rarely found. One study indicates a decreasing number of crashes for an increase of lanes, while the remaining studies indicate the opposite. The difference is caused by the interaction with other variables like annual average daily traffic (AADT), speed limits, lane width, road type and the percentage of heavy good vehicles (HGV). Most of the studies involve Crash Prediction Models (CPMs).

4.5.3 Cross-section deficiencies-Narrow lanes

Full risk factor evaluation can be found in Appendix A.21.

Colour code: Yellow

Research shows that narrow lanes can contribute to either a decrease or increase of crashes. The magnitude of the effect may vary depending on the included covariates and used methods. The degree to which lane width may affect crashes depends upon its interaction with other characteristics of the roadway, specifically, number of lanes and shoulder width. When the variable AADT is taken into account in the model it can be said that it has a negative effect on road safety, whether the individual outcome of the variable narrow lanes is positive or negative.

Abstract

Research shows that narrow lanes can have both positive and negative effects on road safety. The effect of a narrow lane on crashes often concerns only the number of crashes or total crash reduction. A distinction between crash types is rarely found. Some studies indicate that narrow lanes lead to a higher number of crashes while other studies reveal an opposite effect. The difference depends on the circumstances and is the interaction with other variables like annual average daily traffic (AADT), road type, shoulder width and the percentage of heavy good vehicles (HGV). Most of the studies involve Crash Prediction Models (CPMs). When the variable AADT is taken into account in the model it can be said that it has a negative effect on road safety, whether the individual outcome of the variable narrow lanes is positive or negative.

4.5.4 Undivided Road

Full risk factor evaluation can be found in Appendix A.22.

Colour code: Yellow

Undivided roads seem to increase the severity of head-on road crashes. However the effects seem to depend to the type of crash investigated and various external factors (e.g. type of area, road alignment).

Abstract

In general, mixed effects of undivided road on road safety are observed. The identified studies examine the effect of the absence/presence of a median included as a variable in multivariable linear statistical models. Undivided roads appear to not have a significant effect on head-on crash frequency, but increase their severity. Severity of run-off-road (ROR) and pedestrian crashes seems not to be affected, but the number of ROR accidents appears to decrease. Transferability issues may arise as different type of crashes are examined under different conditions.

4.5.5 Cross-section deficiencies - Narrow Median

Full risk factor evaluation can be found in Appendix A.23.

Colour code: Yellow

Most of the studies show that narrow medians seem to increase the number of crashes. However a study found also that narrow medians tend to have lower no-injury crash rates. Another research came to the conclusion that the effect on injury severity of bus crashes is not significant. Overall, it can be concluded that narrow medians are probably risky.

Abstract

Estimates are based on studies that examine the relationship between median width and both frequency and severity of crashes. It appears that the decrease in median width increases crash frequencies. The effect seems to be more pronounced for crashes involvement of female and older drivers. However if median width is less than 40 feet (12 m) the no-injury crash rate appears to decrease. A non-significant effect on injury severity of bus crashes has been found. All studies are from the US.

4.5.6 Shoulder and roadside deficiencies -Absence of paved shoulders

Full risk factor evaluation can be found in Appendix A.24.

Colour code: Red

The absence of (paved) shoulders increases the risk of run-of-road crashes on rural highways. Paved shoulders are likely to reduce total crashes or shoulder-related crashes, but at the same time may increase fatal crashes, suggesting that possible speed increase by paved shoulders may counteract its safety effect. The effectiveness of shoulders in reducing crashes depends upon the interaction with other characteristics of the roadway, specifically the number of lanes, lane widths and traffic volume.

Abstract

A road shoulder is the section of a roadway that lies immediately adjacent to the travelled lane (or driven carriageway). The absence of a paved shoulder has been identified as a risk factor in studies on 2-lane rural highways. Paved shoulders may increase safety by providing a recovery area for drivers who have left the travelled lane and a place for a driver to manoeuvre to avoid crashes. However, shoulders may increase crash risk by conflicts caused by vehicles stopped on the shoulder and by inviting higher speeds. Most studies showed that the absence of paved shoulder was associated with an increase in crashes. One study showed that although the presence of shoulders was associated with decreases in injury and property damage crashes, it was also associated with increases in fatal crashes. Another study showed that the presence of paved shoulders was associated with larger safety effects than the presence of unpaved shoulders. In general, the evidence suggests that paved shoulders reduce total and shoulder-related crashes, but the possible speed enhancing effect of (wide) paved shoulders may increase fatal crashes.

4.5.7 Shoulder and roadside deficiencies -Narrow shoulders

Full risk factor evaluation can be found in Appendix A.25.

Colour code: Red

Narrow(er) shoulders increases the risk of run-off-road crashes on 2-lane rural highways. In general, wider shoulders are associated to lower crash rates. The effect of shoulder width in reducing crashes depends upon its interaction with other characteristics of the roadway, specifically, number of lanes and lane widths.

Abstract

A road shoulder is that section of roadway immediately adjacent to the travelled lane and is generally reserved for use as an emergency lane, on mainland European roads it is located on the right had side of the road. The shoulder can be surfaced or unsurfaced. The lack of adequate shoulder width has been identified as a risk factor in studies on 2-lane rural highways. Paved shoulders may increase safety by providing a recovery area for drivers who have left the travelled lane and they provide a place for a driver to stop a defective vehicle and avoid crashes. However, at the same time, shoulders may to some extent increase the risk of conflicts caused by vehicles stopped on shoulder and by inadvertently inviting higher speeds (wide shoulders and wide lanes lead to a generous cross section). The described effects depend not only on the presence of a road shoulder but also on the width of the road shoulder. A wider road shoulder provides the driver with more recovery area but may trigger higher speeds. Five USA-studies were coded on shoulder width. All five studies showed that wider shoulders were associated with a decrease in crashes. One study also combined the variables shoulder width and the presence of shoulder rumble strips and showed a decrease of the number of crashes. Another study combined the variables shoulder width and speed limit and showed a decrease of crashes for an increase of the shoulder width on roads with a higher speed limit. A third study combined the variables shoulder width and lane width and showed a decrease in the number of crashes. The remaining two studies showed the single effect of shoulder width on the number of crashes. In general, the evidence is conclusive that narrow shoulders increase the number of crashes compared to wider shoulders, be it for different conditions.

4.5.8 Shoulder and roadside deficiencies - Risks associated with safety barriers and obstacles

Full risk factor evaluation can be found in Appendix A.26.

Colour code: Yellow

Most of the studies show that the absence of safety barriers and the presence of obstacles in the roadside seem to affect both the number of crashes and the severity of injuries. Presence and type of obstacle struck and a shortened distance to obstacles tend to increase run-off-road crash frequency and a higher injury risk. However regarding safety barriers, variable effects can be observed.

Abstract

Safety barriers and obstacles refer to: 1) the presence and type of obstacles in the roadside; 2) the distance between the edge of the road and fixed obstacles; 3) the absence of protection from the obstacles. The Synopsis focuses on the risk aspects of safety barriers and obstacles and does not consider the safety benefits from implementing a safety barrier as a countermeasure. In general, mixed effects of safety barriers and obstacles on road safety are observed. Obstacles close to the road can increase the number of crashes, moreover different obstacles lead to different consequences in case of crash. The shorter the distance to the obstacle the higher is the run-off-road crash frequency and the probability of a severe injury accident. The effect of safety barriers on crash frequency seems to be non-significant, while the effect on accident severity seems to be somewhat unclear. If not adequately protected guardrails and concrete barriers may represent a risk for motorcyclists.

4.5.9 Shoulder and roadside deficiencies- sight obstructions (Landscape, Obstacles and Vegetation)

Full risk factor evaluation can be found in Appendix A.27.

Colour code: Yellow

Studies results show that a significant negative effect on road safety is determined only in the presence of a wider tree offset[4]. The results of the studies on speed and lateral position show only effects in terms of increment or reduction of these two parameters, but not in crash rate. Moreover, the effect of sight obstruction has not been tested under all conditions (e.g. investigation of crash severities by different user groups, different road area, no European studies found, etc.).

Abstract

Roadside elements like vegetation, trees, fixed-objects and landscape play a crucial role in the outcomes of loss-of-control and run-off-the-road crashes and severities. Additionally, they influence the way drivers perceive the road edge and alignment and therefore behaviour. Moreover, some studies show how widening paved shoulders, widening fixed-object offsets, and livable-streets[5] can also influence the number of crashes and severities. Driver lateral position, speed, and both crash rate and severity are the effects studied. Speed and lateral position results show that drivers significantly decrease their speeds and move toward the centreline of the road when roadside trees are nearer to the edge of the road. Concerning crashes rate and severity decrease significantly in livable streets. Most of the International studies did not identify differences between junctions and roads.

The main statistical method applied in investigating the relationship between such sight obstructions and speed/lateral position was analysis of variance (ANOVA). While, to study the link between crash rate and landscape design elements was used the before-after (landscape treatments) analysis and negative binomial regression models.

The studies analysis were focused on urban, suburban and rural road network. Most research was done in United States and only one in Europe (Italy).

4.6 ALIGNMENT - JUNCTIONS

4.6.1 Interchange deficiencies- ramp length

Full risk factor evaluation can be found in Appendix A.28.

Colour code: Yellow

In general, mixed findings were observed, however ramp length is probably risky. While three studies indicate that increased ramp length leads to more serious crashes (an increase in injury severity), the results are not consistent when crash frequency is examined. In this case, four studies were identified with contradictory results; one with positive effect (decrease crashes), two with negative effect (increase crashes) and one with non-significant effect.

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[4] Two offsets of the trees from the edge of the road pavement

[5] livable streets, at a minimum, seek to enhance the pedestrian character of the street by providing a continuous sidewalk network and incorporating design features that minimize the negative impacts of motor vehicle use on pedestrians (Duany et al., 2000; Ewing, 1996; Jacobs, 1961)

Abstract

In general, short ramps may cause crashes because in this case the driver does not have the time to adjust their speed appropriately. Ramp length is probably risky for road safety although some mixed findings were observed. The results can be differentiated between effects on crash severity and crash frequency. The studies indicate that increased ramp length leads to more serious crashes (i.e. an increase in injury severity) but the results are significant only at 90% confidence level. The meta-analysis that was conducted revealed a non-significant overall effect for a 95% level. The impact of ramp length on crash frequency is unclear, as two studies indicate that an increase in ramp length leads to more crashes, but opposite or non-significant effects were also found.

4.6.2 Interchange deficiencies-Acceleration/Deceleration lane length

Full risk factor evaluation can be found in Appendix A.29.

Colour code: Grey

The effect of acceleration and deceleration lane length on road safety is unclear and needs further investigation. The main reason is that mixed effects appear to exist in literature. Firstly, the influence on the number of crashes is unclear as studies show inconsistent findings. On the other hand, it is suggested that increased length of deceleration lanes results in lower crash severity (less severe crashes). However the impact of acceleration lanes has not investigated yet.

Abstract

Overall, acceleration and deceleration lane lengths were found to have inconsistent and mixed influence on road safety. It is noted that the majority of studies focus on deceleration lanes on freeway exit areas. The majority of relevant literature investigates the number of crashes, suggesting that the effect is not clear. Nevertheless, most recent studies indicate that increased deceleration lane length leads to more crashes (although less severe). The meta-analysis that was carried out confirmed the inconsistent findings as a non-significant effect of the overall estimate of deceleration lane length was found at a 95% level. Furthermore, it was also attempted to perform a meta-analysis on the basis of two studies examining the impact of deceleration lane length on crash severity, suggesting a non-significant effect. However, due to the fact that only two studies were included in this meta-analysis the results should be interpreted with care. In conclusion, the inconsistent findings of international literature clearly suggests that further research is need on this topic.

4.6.3 At-grade junctions deficiencies-Number of conflict points

Full risk factor evaluation can be found in Appendix A.30.

Colour code: Yellow

The number of conflict points at junctions, which is mostly expressed through the (total) number of lanes – appears to have a negative effect on road safety. However, some studies – especially for specific crash types – show different effects. Thus, whereas a higher number of conflict points tends to increase crash risk in general, it might be that for specific crash types an additional lane - and with it an addition of conflict points - could nevertheless probably reduce crash risk.

Abstract

The number of conflict points at junctions, which is mostly expressed (total) number of lanes – – appears to deteriorate road safety. Studies on crash frequency mostly indicate that an increase of the number of lanes and therefore an increase in the number of conflict points tends to increase crash frequency, or that junctions with less lanes (and therefore less conflict points) tend to have lower numbers of crashes in general. Furthermore, some studies show this tendency for specific types of lanes (e.g. number of left-turn lanes in right-driving countries) as well as for specific crash types (e.g. angle-crashes). However some studies – especially for specific crash types (e.g. rear-end crashes) – show different effects. Summarizing, in general it appears that an increase of the number of conflict points tend to increase crash frequency, however for some crash types (e.g. rear-end crashes) an additional lane which is connected with additional conflict points could nevertheless probably reduce crash risk.

4.6.4 Risks of different junction types

Full risk factor evaluation can be found in Appendix A.31.

Colour code: Yellow

From the effects of the type of junction (constructional, not signalisation) on road safety presented in international literature it seems that junctions with more approaches/arms like crossroads (4 arms) or multiple (>4 arms) have higher crash risks and lead to a higher crash severity compared to 3-legged junctions (T-junctions).

Abstract

Regarding the effect of the type of junction on road safety, studies on accident frequency mostly show a higher crash risk for junctions with four or more arms compared to 3-legged junctions. Those effects were often statistically significant. Furthermore, studies on crash severity mostly indicated that junctions with four or more legs increase crash severity compared to 3-legged junctions. Summarizing, it seems that junctions with more approaches/arms like crossroads (4 arms) or multiple (>4 arms) have higher crash risks and lead to a higher crash severity compared to 3-legged junctions (T-junctions). Also compared to roundabouts, other junctions tend to have a higher crash risk in general. Roundabouts can significantly reduce the severity of accidents.

4.6.5 At-grade junction deficiencies - skewness / junction angle

Full risk factor evaluation can be found in Appendix A.32.

Colour code: Yellow

Most of the studies show that if roads intersect at a skewed angle (not at right angles) there is an increase to the crash risk. These results in most of the cases were statistically significant. However, for specific types of crashes such as rear-end crashes varied effects were observed. Furthermore a skewed angle probably leads to more serious crashes (statistically significant results), however also non-statistically significant opposite effects on accident severity have been reported as well.

Abstract

Regarding the risk of skewness at an intersection, it can be observed that most studies on crash frequency show that a skewed angle (not at right angles) at intersections leads to a higher crash risk compared to an intersection with road intersecting at right angles (or close to that). Furthermore it also appears that a skewed angle at junctions leads to more serious crashes (i.e. an increase of injury severity) – in most cases the area type was not specified. Results showing these tendencies were statistically significant in most studies, however a few studies presented varying effects for crash risk for specific crash types, such as rear-end crashes, although mostly not statistically significant. Thus a skewed angle at junctions appears to lead to a higher crash risk and probably to more serious crashes in general. Age and road user type (truck driver) influence the effect of skewness considerably. For instance skewed intersections can pose problems for older drivers because of their decline in head and neck mobility.

4.6.6 At-grade junctions deficiencies-poor sight distance

Full risk factor evaluation can be found in Appendix A.33.

Colour code: Yellow

Most of the studies on (poor) sight distance at junctions show an elevated crash risk. For example, the restriction of field of view leads to more crashes. At the same time some of the estimates are not statistically significant and furthermore two studies delivered contrary results, which showed that decreased sight distance may decrease crash occurrence. Despite those, it can be concluded that poor sight distance is probably risky.

Abstract

Poor sight distance at junctions can affect road safety, as it results in other road users and/or obstacles not being detected soon enough for the driver to safely stop the vehicle. Hence, an adequate field of view is of great importance, especially when operating speeds are high. Though it is unclear if and how (poor) sight distance influences the crash risk at junctions. Most of the studies show a correlation between restricted sight distance and crash occurrence but only a few of them delivered significant results. At the same time two studies showed very interesting contrary estimates, which might be due to higher speeds chosen when there is a better view provided – increases in the sight distances may allow drivers to have greater freedom of manoeuvre. The main approach used to investigate the relationship between sight distance and crash risk was regression analyses. Sight distance was often one factor considered as part of investigations considering a range of factors which influence road safety. One study used a driving simulator rather than real driving approach. Most research was done in Singapore but also in the United States and China. The majority of the studies investigated junctions on urban roads.

4.6.7 At-grade junction deficiencies - gradient

Full risk factor evaluation can be found in Appendix A.34.

Colour code: Yellow

Effects of gradients at junctions with regards to crash frequency (or crash risk) are somewhat variable. However, studies on crash severity indicated that intersections with gradient increase the risk of more severe accidents (i.e. an increase to injury severity) in general. At the same time gradients at junctions appear to only increase the crash risk for specific crash types (especially rear-end crashes).

Abstract

Regarding the effect of gradient at junctions on road safety, studies on accident frequency show partly variable effects of gradients. While some studies on crash frequency indicated that junctions with gradient increase crash risk compared to junctions without gradient for specific crash types (particularly rear-end accidents), some studies also showed some contrary results. Studies on crash severity indicated that junctions with gradient increase the risk for more severe accidents, with this being the case for downhill approaches (high-speed crashes) as well as uphill approaches. In summary, gradients at junctions appear to only increase crash risk for specific crash types (especially rear-end crashes), but they tend to lead to more severe crash (i.e. an increase to injury severity) in general.

4.7 TRAFFIC CONTROL - JUNCTIONS

4.7.1 Uncontrolled Rail-Road Crossing

Full risk factor evaluation can be found in Appendix A.35.

Colour code: Yellow

In general, it can be summarised that uncontrolled rail-road crossings tend to have a higher crash risk compared to rail-road crossings equipped with (active) control devices. Thus, rail-road crossings with active control devices have positive effects on road safety. Furthermore partly also variable effects are presented.

Abstract

From the studies identified in the international literature it appears that uncontrolled/passive rail-road crossings are associated with a higher crash risk compared to rail-road crossings equipped with active control devices. Also the risk for a more severe injury crash at uncontrolled/passive rail-road crossings is higher than at rail-road crossings with active warning devices. Further the studies identified partly show variable effects and also national specifications regarding the different control types which play a role for the effects estimated in the studies as well.

4.7.2 Poor junction readability-Uncontrolled junctions

Full risk factor evaluation can be found in Appendix A.36.

Colour code: Yellow

Uncontrolled junctions are probably risky as crashes tend to be more severe. However, some studies indicate that the total number of crashes at uncontrolled junctions are fewer than at controlled junctions. This result could be attributed to exposure as traffic is lower and fewer pedestrians cross at uncontrolled junctions. A number of studies indicate that most mid-block crashes occur near uncontrolled junctions. Overall, it can be thus argued that fewer but more severe crashes occur at uncontrolled junctions.

Abstract

Overall, the effect of uncontrolled junctions on road safety was not entirely clear however, it can be considered risky. Some counterintuitive findings also exist in literature. More specifically, literature suggests that fewer crashes occur at uncontrolled junctions. This could be attributed to limited exposure at these areas and to the fact that a portion of crashes with pedestrians that might have occurred at uncontrolled junctions actually occur at mid-block locations, because pedestrians choose to cross before reaching a junction. On the other hand, it was found that crashes at uncontrolled junctions tend to be more severe, but not always when crash types are examined separately. The vote count analysis that was carried out on the basis of 8 coded studies confirms this tendency. It is noted that most of literature explores the effect of various traffic control measures of junctions on safety rather than the risk of uncontrolled junctions.

4.7.3 Poor junction readability - absence of road markings and crosswalks

Full risk factor evaluation can be found in Appendix A.37.

Colour code: Yellow

From studies on the effects of the absence of road markings and crosswalks at junctions it appears that the lack of these features (e.g. stop lines) may lead to more severe accidents. However, for studies considering crash risk, variable effects for the absence of road markings and crosswalks can be observed.

Abstract

Regarding the effects of absence of road markings and crosswalks on road safety, it can be observed that studies on crash frequency show differing results: some studies indicate a higher crash risk at junctions where road markings or crosswalks are absent, however other studies also show contrary results. Studies on crash severity mainly show a (significant) higher injury severity at junctions without markings or crosswalks. Thus junctions without road markings and crosswalks tend to lead to more severe crashes in urban as well as in rural settings.

5 Conclusions

This chapter provides an overview of the findings from the evaluation of road infrastructure risks. This includes a ranking of risk factors by the level of evidence of risk to road safety, limitations of the process and summary of the next steps for the infrastructure related work of the SafetyCube project.

5.1 RANKING OF RISK FACTORS

For each specific risk factor of the infrastructure taxonomy, a systematic search of the literature was undertaken. The identified relevant studies were coded using a uniformed 'coding template'. This captured **quantifiable objective findings about crash risk, frequency and severity influenced by the risk factor**. Where sufficient studies could be identified, a synopsis was written summarising the impact of the risk factor on road safety. Each synopsis has a common format which starts with a colour code indicating the level of evidence available as to the risk imposed. This is followed by an abstract providing a summary of the findings for this risk factor. The full synopsis for each risk factor can be found in the appendix to this report.

Table 11 presents the risk factors separated by colour code. In total 8 risk factors were given the colour **Red, indicating that there is consistent evidence** that this risk factor has a negative effect on road safety in terms of increasing crash risk, frequency or severity. The specific risk factors in the red category are distributed across a range of infrastructure elements, demonstrating that the greatest risk is spread across several aspects of the taxonomy. This is a particularly important finding for the following risky factors, as these were also identified as hot topics:

- Presence of work zones-Workzone length
- Alignment deficiencies-Low curve radius
- Shoulder and roadside deficiencies -Absence of paved shoulders
- Shoulder and roadside deficiencies -Narrow shoulders

It is interesting to note that **some risk factors allocated a Red colour code were not identified by stakeholders as being hot topics**. This suggests that there is a degree of discordance between stakeholder perception or opinion of which infrastructure factors pose most risk and the scientific evidence. This may be due to the fact that different stakeholders may have different specific areas of interest, and therefore not all risk factors are of equal importance to all stakeholders. Alternatively, stakeholders may be aware of the risk but feel it is already controlled for in their specific area of activity, or not possible to control for.

A further 20 risk factors were considered to be **Yellow demonstrating some evidence of impact to road safety**, however, problems of weak findings, inconsistency between studies or few studies means that the evidence for risk was not considered sufficient to be coded Red. More risk factors were coded Yellow than any other rating. This likely reflects the growing field of road safety research. It is very likely that these are risky but at the moment not enough research of high quality has been conducted to confirm this. Several risk factors allocated a Yellow colour code are hot topics.

Seven risk factors were considered to be **Grey indicating that there was not enough evidence to draw a clear conclusion** about their impact on road safety. This represents a gap in road safety scientific literature. It would be beneficial for future research to consider addressing each of these factors. This is a particular problem because some of the Grey colour coded risk factors are hot topics. This demonstrates that the scientific literature is not currently meeting all the needs of road safety stakeholders for evidence-base.

Table 11: Infrastructure related risk factor synopses by colour code

Red (Risky)	Yellow (Probably risky)	Grey (Unclear)
! Effect of Traffic Volume on safety ! Risks associated with Traffic Composition ! Road Surface - Inadequate Friction ! Workzone length ! Alignment deficiencies - Low Curve Radius ! Cross-section deficiencies - Number of Lanes ! Shoulder and roadside deficiencies -Absence of paved shoulders ! Shoulder and roadside deficiencies - Narrow Shoulders	! Occurrence of Secondary crashes ! Alignment deficiencies - Absence of Transition curves ! Risk of Different Road Types ! Adverse weather - Rain ! Poor Visibility - Darkness ! Cross-section deficiencies - Superelevation ! Alignment deficiencies - High grade ! Presence of Tunnels Cross-section deficiencies - Narrow lanes ! Undivided road ! Cross-section deficiencies - Narrow median ! Shoulder and roadside deficiencies - Risks associated with Safety Barriers and Obstacles ! Shoulder and roadside deficiencies - Sight Obstructions (Landscape, Obstacles and Vegetation) ! Interchange deficiencies - Ramp Length ! At-grade junctions deficiencies - Number of conflict points ! Risk of different junction types At-grade junction deficiencies - Skewness / Junction angle ! At-grade junction deficiencies - Poor sight distance ! At-grade junction deficiencies - Gradient ! Uncontrolled rail-road crossing ! Poor junction readability - Absence of road markings and crosswalks ! Poor junction readability - Uncontrolled junction	? Congestion as a risk factor ? Risks associated with the distribution of traffic flow over arms at junctions ? Adverse weather - Frost and snow ? Workzone duration ? Alignment deficiencies - Frequent curves ? Alignment deficiencies - Densely spaced junctions ? Interchange deficiencies - Acceleration / deceleration lane length

An overview of the infrastructure related road safety problems is presented in **Table 12**. Results are separated for each of the infrastructure element, with the specific risk factors within each element **ranked by colour code and indication on the type of road safety outcomes affected, as well as whether or not this is a hot topic**. The infrastructure elements Exposure and Cross-Section Road Segments have the greatest number of specific risk factors with a Red colour code.

Table 12 Overview of infrastructure related problems and associated risk to crashes

Infrastructure Element	Specific Risk Factor	Colour code	Crash risk	Crash frequency	Crash severity	Hot topic (Yes/No)
Exposure	Effect of Traffic Volume on safety	Red	↓	↑	-	N
	Risks associated with Traffic Composition	Red	↓	↑	-	N
	Occurrence of Secondary crashes	Yellow	↑	-	-	N
	Congestion as a risk factor	Grey	-	↑	-	N
	Risks associated with the distribution of traffic flow over arms at junctions	Grey	-	-	↑	N
Road Surface	Inadequate Friction	Red	↑	-	↑	N
Road Type	Risk of Different Road Types	Yellow	-	↑	↑	N
Road environment	Adverse weather - Rain	Yellow	-	↑	-	N
	Adverse weather - Frost and Snow	Grey	-	-	-	N
	Poor Visibility - Darkness	Yellow	↑	-	↑	N
Presence of workzones	Workzone Length	Red	↑	↑	-	Y
	Workzone Duration	Grey	-	-	-	Y
Alignment - Road Segments	Low Curve Radius	Red	-	↑	↑	Y
	Alignment deficiencies - Absence of transition curves	Yellow	↑	-	-	Y
	Alignment deficiencies - High Grade	Yellow	-	↑	↑	Y
	Presence of Tunnels	Yellow	-	↑	↑	Y
	Alignment deficiencies - Frequent curves	Grey	-	-	-	Y
	Alignment deficiencies - Densely spaced junctions	Grey	-	-	-	Y

Cross-Section - Road Segments	Cross-section deficiencies - Number of lanes	**Red**	-	↑	↑	N
	Shoulder and roadside deficiencies -Absence of paved shoulders	**Red**	-	↑	-	**Y**
	Shoulder and roadside deficiencies -Narrow shoulders	**Red**	-	↑	-	**Y**
	Cross-section deficiencies-Narrow lanes	**Yellow**	-	↑	-	N
	Undivided Road	**Yellow**	-	-	↑	N
	Cross-section deficiencies - Narrow Median	**Yellow**	-	↑	↑	N
	Shoulder and roadside deficiencies - Risks associated with safety barriers and obstacles	**Yellow**	-	↑	↑	**Y**
	Shoulder and roadside deficiencies- sight obstructions (Landscape, Obstacles and Vegetation)	**Yellow**	-	-	-	**Y**
	Cross-section deficiencies - Superelevation	**Yellow**	↑	↑	-	N
Alignment - Junctions	Interchange deficiencies- ramp length	**Yellow**	-	-	↑	N
	At-grade junctions deficiencies-Number of conflict points	**Yellow**	-	↑	-	**Y**
	Risk of different junction types	**Yellow**	↑	-	↑	**Y**
	At-grade junction deficiencies - skewness / junction angle	**Yellow**	↑	-	↑	**Y**
	At-grade junction deficiencies - Poor Sight Distance	**Yellow**	↑	-	-	**Y**
	At-grade junction deficiencies - gradient	**Yellow**	↑	-	↑	N
	Interchange deficiencies-Acceleration/Deceleration lane length	**Grey**	-	-	-	N
Traffic Control - Junctions	Uncontrolled Rail-Road Crossing	**Yellow**	↑	-	↑	N
	Poor junction readability - absence of road markings and crosswalks	**Yellow**	-	-	↑	N
	Poor junction readability-Uncontrolled junctions	**Yellow**	-	↓	↑	N

Unfortunately it was not possible to produce a synopsis for all specific risk factors listed in the taxonomy (see section 3.5). This was due to difficulties of finding enough relevant studies. Often this was due to the absence of an infrastructure element or with a strong association with a measure/solution to improve road safety e.g. insufficient signage in workzones. These topics will be dealt with as part of WP5.2 which deals with the relationship between crashes effects resulting from treatments/measures deployed to improve road infrastructure defects or problems.

The following specific risk factors were identified as hot topics by stakeholder but not have a synopsis:

- Insufficient signage (Presence of workzones)
- Vertical curve radius (Alignment – Road segments)
- Poor sight distance – vertical curve (Alignment – Road segments)
- Poor road readability (Traffic control – road segments)
- Misleading or unreadable traffic signs (Traffic control – junctions)

This demonstrates that **there are some emerging issues for road safety practitioners and policy makers which the scientific community has not yet adequately investigated**. Although there is not enough evidence to produce a synopsis for each of these risk factors, in some cases there are a few studies. If this is the case (as with insufficient signage at workzones) the individual studies have been coded and included in the DSS. This will give DSS users access to as much information as is currently possible, even though it is not meaningful to summarise this information.

Poor road readability is an example of a risk factor which is commonly investigated by evaluating the impact of a treatment/measure to improve road readability. As such, this infrastructure element will be considered in detail as part of the measures analysis.

5.2 LIMITATIONS

The limitations of this work should be noted. The process of **allocating colour codes was related to both the magnitude of risk observed and the level of evidence** for this. It is possible for a risk factor with a yellow colour code to have a greater impact on road safety (e.g. increased severity of crashes) than a risk factor coded red, if there was limited evidence of its risk. Because of this it is important to recognise that road safety benefits may be expected from implementing measures to mitigate any red or yellow coded infrastructure risks.

Findings are limited both by **the implemented literature search strategy and the quality of the studies identified**. The specific search strategy for each risk factor is explained in the supporting document of each synopsis in the appendix. However, since this deliverable focusses on infrastructure, a common approach using the TRID search database was adopted since this is a rich source of information for research into the relationship between infrastructure design and layout and crashes/safety. However, TRID is an American database which may have artificially increased the number of American studies reviewed. Nevertheless, the studies identified were of sufficiently high quality to inform understanding of the risk factor.

Due to resources constraints, prioritising of study coding was necessary for risk factors with many identified studies. The **criteria for prioritising** within each synopsis is detailed in the supporting document. Across all risk factors, priority was given to studies which considered crashes over changes in driving behaviour or effects of safety performance indicators such as speeds. This approach focused on studies with the highest methodological quality, however, it is possible that some detail of level of risk may have been missed by failure to consider a broad range of methodological approaches. Finally, within the considered literature, crash risk and crash frequency are much more commonly studied than crash severity. For some risk factors this makes it difficult (or impossible) to consider the implications for injury causation.

5.3 NEXT STEPS

5.3.1 Input to the SafetyCube DSS

The coded studies and synopses for the infrastructure risk factors will be accessible to the users of the DSS. The colour code for each specific risk factor will be clearly presented within the DSS itself. Users will have the option to undertake a search of the DSS in several ways. Regardless of the type of search (entry point from which a user enters the DSS) results will always be presented in a consistent manner. This includes one page per infrastructure element (possibly thus presenting more than one specific risk factor on the same page). On the main infrastructure element page, each specific risk factor will be presented along with their colour code.

There will be options for reducing the number of specific risk factors presented by using a search filter system. By presenting specific risk factors grouped by infrastructure element in this way there will be opportunity to draw user attention to other risk factors they might not have considered. For example, if a user were to search for narrow lanes the results page generated would also give them the option to see other Cross-Section – Road Segment related specific risk factors. From this they may realise that there is greater evidence for the risk for narrow shoulders. When deciding how to allocate limited resources for improving road safety, awareness of the relative evidence for risk of each factor is likely to assist in decision making.

For details on the way the results in the present report will be integrated / presented in the DSS, please see Deliverable 8.1 of SafetyCube.

5.3.2 Analysis of infrastructure measures

The next task of SafetyCube is to begin identifying measures that will counter the identified risk factors, in this case those that relate to infrastructure. Methodological guidance has been provided for this task as part of Deliverable 3.3 (Martensen et al., 2017). This notes that not all risk factors are equally mitigated for by implementation of road safety measures. Furthermore, it is vital that the appropriate measure is applied to the appropriate risk factor. This may not be within the same aspect of the road system, for example an infrastructure risk such as frost and snow may be mitigated by a vehicle related measure such as winter tyres.

The next step in Task 5.2 will be to identify the infrastructure measures that can counter the risks identified in the current document, summarise their safety effects in a similar way that the risks were summarised, and subsequently evaluate their cost-benefit and cost-effectiveness within Task 5.3. As the road network is an interactive system between road users, infrastructure and vehicles interventions, measures and solutions to road safety risk will be considered across all components of the road system. Priority will be placed on investigating measures aimed at mitigating the risk factors identified as Red. The subsequent priority of risk factors in the Yellow category will depend on why they were assigned to this category and whether or not they are a hot topic. Those risk factors with a lot of consistent but weak evidence of risk will be prioritised over those with little or highly inconsistent evidence. Those which are hot topics will be prioritised over those which are not. However, measures for all risk factors will be examined overall.

The studies coded and synopses produced as part of this deliverable (see appendix) will be integrated within the Decision Support System (DSS) being developed for the SafetyCube project. This will help enable road safety practitioners and other stakeholders better understand risks, select and implement the most appropriate strategies, measures and cost-effective approaches to reduce casualties of all road user types and all severities. The dynamic interface of the DSS will allow end users to easily navigate between risk factors and measures both within a road safety area (e.g.

Infrastructure) and between areas. The integrated Safe Systems Approach of the DSS will facilitate understanding of how infrastructure related problems and solutions interact with both road user behaviour and vehicles.

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Appendix A

This appendix includes all the infrastructure synopses that are available in October 2016. These will be available through the DSS when it is launched in 2017. The synopses are intended to be periodically updated to reflect new research or in some cases to expand their scope. Future updates or additions to the synopses will be available on the project website (http://www.safetycube-project.eu/) and the DSS. The order of synopses follows the taxonomy as in the Chapter 4 of the Deliverable, namely:

1. Effect of traffic volume on road safety
2. Congestion as a risk factor
3. Occurrence of Secondary crashes
4. Risks associated with varying traffic composition
5. Risks associated with the distribution of traffic flow over arms at junctions
6. Risk of Different Road Types
7. Road Surface Deficiencies - Inadequate Friction
8. Adverse weather conditions – Rain
9. Adverse weather conditions – Frost & Snow
10. Poor visibility-Darkness
11. Workzone Length
12. Workzone Duration
13. Alignment deficiencies-Low curve radius
14. Alignment deficiencies - Absence of transition curves
15. Alignment deficiencies - Frequent curves
16. Alignment deficiencies - Densely spaced junctions
17. Alignment deficiencies - High Grade
18. Presence of Tunnels
19. Cross-section deficiencies - Superelevation
20. Cross-section deficiencies - Number of lanes
21. Cross-section deficiencies-Narrow lanes
22. Undivided Road
23. Cross-section deficiencies - Narrow Median
24. Shoulder and roadside deficiencies -Absence of paved shoulders
25. Shoulder and roadside deficiencies -Narrow shoulders
26. Shoulder and roadside deficiencies - Risks associated with safety barriers and obstacles
27. Shoulder and roadside deficiencies- sight obstructions (Landscape, Obstacles and Vegetation)
28. Interchange deficiencies- ramp length
29. Interchange deficiencies-Acceleration/Deceleration lane length
30. At-grade junctions deficiencies-Number of conflict points
31. Risk of different junction types
32. At-grade junction deficiencies - skewness / junction angle
33. At-grade junctions deficiencies-poor sight distance
34. At-grade junction deficiencies - gradient
35. Uncontrolled Rail-Road Crossing
36. Poor junction readability-Uncontrolled junctions
37. Poor junction readability - absence of road markings and crosswalks

Synopsis 1: Effect of traffic volume on road safety

1 Summary

Hesjevoll, I.S. & Elvik, R., August, 2016.

COLOUR CODE: RED

Explanation: Most of the reviewed studies find higher traffic volumes to be associated with a net increase in crashes, but a crash increase less than proportional to traffic volume increases, indicating a lower risk for each road user. However, the effect of traffic volume on crash occurrence appears to differ between crash types (e.g. single-vehicle and multi-vehicle crashes).

KEYWORDS

Traffic flow; traffic volume; hourly volume; AADT; annual average daily traffic

1.1 ABSTRACT

Traffic volume, or traffic flow, denotes the number of vehicles passing a given point or section of a road for a given time unit. The relationship between crashes and traffic volume appears to be non-linear. Most reviewed studies find that higher traffic volumes are associated with a net increase of crashes. The number of crashes increases less than proportionally to traffic volume. This indicates that an increase in traffic volume is associated with a lower risk for each road user (since risk = crashes/exposure). Several studies find that the effect of traffic volume on crash occurrence differs between crash types. For multi-vehicle crashes, most studies indicate that both the frequency *and* the risk of such crashes increase at higher traffic volumes. While it seems clear that traffic volume is related to crash occurrence, the form of this relationship (which might differ for different crash types), and the mechanism explaining these relationships remain somewhat unclear. It is also not clear how traffic volume affects road safety on different road types.

1.2 BACKGROUND

1.2.1 What is traffic volume, and how is it measured?

Traffic volume is the number of vehicles passing a cross section during a certain period (e.g. one hour, 5 minutes, or a day). Average annual daily traffic (AADT) is the number of vehicles passing a road in a year, divided by 365. Traffic volume estimates can be based either on continuous counting (traffic sensors), or short-term data collection adjusted for relevant variations (e.g. seasonal, weekday and hourly variations).

1.2.2 How does traffic volume affect road safety?

The mechanism relating traffic volume to crash occurrence is not clear. That is, while an increased traffic volume may lead to a net increase in crashes due to the presence of more vehicles (i.e. more crash candidates), it is not clear how the risk for each individual road user is affected by the total traffic volume. It has been proposed that it is not the number of vehicles per se, but the number of events (e.g. encounters) that is responsible for an association between exposure and crash occurrence (Elvik, 2015). Alternatively, driver alertness could be affected by traffic volume.

1.2.3 What road safety outcomes are affected by traffic volume?

Most reviewed studies investigate how traffic volume relate to crash counts, which is in some cases differentiated for different crash types (e.g. single-vehicle and multi-vehicle, or different severities). Other studies address how crash risk (the number of crashes divided by traffic volume) is affected by traffic volume.

1.2.4 How is the effect of traffic volume on road safety studied?

Two main types of methodologies are used to investigate the relationship between traffic volume and road safety. First, studies investigating the association between traffic volume and crash frequency are generally observational, cross-sectional studies employing multivariate models. The reviewed studies that fall into this category rely on aggregate traffic volume measurements (mostly AADT). A second main category of studies use a case-control design, comparing traffic conditions directly before crash occurrence (cases) to traffic conditions of non-crashes (controls). These studies typically rely on disaggregated, real-time data, and investigate both traffic volume and other traffic characteristics (e.g. occupation, speed). Most studies are based on motorways.

1.3 OVERVIEW OF RESULTS

Seven studies were coded for this risk factor. Among these were two meta-analyses based on studies comparing traffic volumes directly prior to crashes with volumes of non-crash controls.

1.3.1 Main results

The meta-analyses report contradictory results: One finds that higher volume downstream is associated with increased risk of crash occurrence, while the other finds the opposite. The main findings of the remaining studies are:

- Increased traffic volume is generally associated with increased crash occurrence, when all crashed are considered jointly.
- Most studies find increased traffic volume to be associated with a crash increase that is less than proportional to the traffic volume increase, which translates to a lower risk per road user at higher traffic volumes.
- The relationship between traffic volume and crash occurrence is different for different types of crashes. Results for Single-vehicle crashes are mixed. Multi-vehicle crashes appear to increase more than proportional to traffic volume (increased risk).
- Both the direction and the form of the relationship between traffic volume and crash numbers might differ between crash types.

Additionally, relevant results from studies primarily dedicated to other risk factors find that a higher AADT in work zones is associates with negative road safety outcomes, and in ramp/merging/ diverging areas, higher AADT on both the mainline and on the ramp is associated with increased crash occurrence, although in many cases lower risk.

1.3.2 Transferability

Most studies are based on major roads, leaving uncertainty regarding the effect of traffic volume on road safety for different road types. The summarized studies are mainly concerned with motor vehicles (all considered jointly), and the present tendencies might not hold for different road users (the volumes of (conflicting) flows of cyclists, pedestrians, and cars are dealt with in a synopsis on traffic composition). One might expect the effect of traffic volume on road safety to depend on factors such as road type, road capacity, weather, and other traffic characteristics (e.g. density, speed). The effect of AADT on road safety might also depend on how the traffic is distributed (e.g. if it is concentrated in peak-hours, or more continuous throughout the day).

1.4 NOTES ON ANALYSIS METHODS

While it seems clear that traffic volume is related to road safety, some limitations in the reviewed studies should be noted. Many studies rely on aggregate measures, which cover different levels of other risks (e.g. weather, lighting) that are often not accounted for. Furthermore, many studies do not distinguish between different crash types that are shown to relate differently to traffic volume, which could give a simplified or distorted picture of the actual associations of interest. The effect of traffic volume on real-time crash risk remains unclear, and more research in this area would be beneficial.

2 Scientific overview

2.1 LITERATURE REVIEW

2.1.1 On the measurement of traffic volume.

Traffic volume has been investigated on several levels of aggregation, including hourly and daily volumes, and 5-minute intervals. In investigating relationships between crashes and traffic volume, average, aggregated measures such as AADT (and to a lesser degree hourly averages), could be problematic in the sense that they "smooth out" variations and differences that could contribute to the actual crash. For instance, traffic variations over days, weeks, seasons and also over shorter time periods are covered up, and average traffic volumes will often differ from volumes at crash occurrence(s). Additionally, average daily traffic includes variations in other variables known to affect road safety (i.e. that are associated with different levels of risk), such as lighting conditions and weather. The distribution of traffic, e.g. if a given AADT is concentrated in peak hours or spread out more continuously, could also have different implications for road safety, but this is often not accounted for. In sum, this means that average daily measurement does not necessarily capture relevant traffic conditions, and this aggregation of traffic states and levels of other risk factors could produce biased results in investigating the relationship between traffic volume and road safety. For an in-depth explanation of issues arising in averaging traffic volume, see e.g. Mensah & Hauer (1998)

On the other hand, real-time traffic data is associated with different issues and potential biases, e.g. related to the placement of measurement devices (varying distances could mean one has to estimate traffic conditions, and could introduce statistical noise), missing or erroneous data, and temporal placement of crashes from imprecise police reports.

2.1.2 On mechanisms relating traffic volume to road safety

There seems not to be any generally accepted theory relating traffic volume, or exposure, to road safety. Elvik (2015) proposes that it may not be traffic volume as such, but rather the number of events (e.g. encounters, lane changes, overtaking) that is important for road safety. According to Elvik, the number of encounters will increase more rapidly than the AADT, and the repeated experience of a certain type of traffic event will be associated with learning, so that road users become increasingly competent in understanding and controlling the events. Another probable mechanism is the influence of traffic volume on driver alertness: on roads with higher traffic flows, drivers are constantly reminded of the presence of other vehicles, and more easily pay attention to them.

It might also be that for traffic volumes approximating congestion, reduced speed could mean that crashes become less severe. For instance, Golob et al. (2008) find that controlling for whether the traffic state is congested or free flow, a higher traffic volume is associated with a lower likelihood of crashes being injury crashes (vs PDO), which they suggest might be explained by lower speed as traffic becomes denser. This has not been investigated by any other of the reviewed studies. Congestion as a risk factor is treated in a separate synopsis (most congestion studies are conducted on motorways, where speed could remain high even in congested states, and so there is limited evidence for congestion reducing crash severity in studies reviewed for congestion), and with the exception of case-control studies, the studies reviewed for traffic volume generally do not take congestion or speed into account.

More generally, two identified reviews note that the effect of traffic volume could depend on weather conditions (Theofilatos & Yannis, 2014) and other traffic characteristics (such as speed and density) (Wang, Quddus, & Ison, 2013), which is not taken into account in most reviewed studies.

2.2 DESCRIPTION OF STUDIES

2.2.1 How is the effect of traffic volume studied?

Two types of original studies are found among the articles in this review. First, one type of study aims to identify traffic conditions associated with increased crash occurrence by comparing traffic conditions prior to crashes with those of non-crash control periods. These studies typically rely on real-time traffic data, aggregated to 5-minute intervals. The majority of primary studies on which the meta-analyses are based, as well as one section of an original study, fall into this category. Both meta-analyses focus on general/all crashes, and neither distinguished between different crash severities, and they include some of the same studies. One meta-analysis applies Bayesian meta-analysis methods (several varieties, including Bayesian meta-regression), while the other applied inverse variance meta-analysis, with fixed and random effects.

The second category of studies are cross-sectional studies that rely on multivariate crash prediction models to explain variation in crash numbers between locations (and in some instances across time units) by traffic volume, and the models often include other factors as well. The analyses applied are mostly count regression models (negative binomial, generalized negative binomial, zero-inflated Poisson, and Bayesian bivariate Poisson-lognormal). All five original studies coded primarily for traffic volume fall into this category. Three out of five studies model single-vehicle (SV) and multi-vehicle (MV) crashes separately (Lord et al., 2005; Yu & Abdel-Aty, 2013; Qin et al., 2004), and one of these also draw distinctions between different types of MV crashes. Two studies provide estimates of crash frequency per crash severity (Caliendo et al., 2007; Lord et al., 2005), and one study also looks into crash involvement for different driver demographics (Abdel-Aty & Rawdan, 2000). Most of these studies investigate AADT, but some make distinctions between AADT per lane and/or direction while others do not (or do not report if they do). One study investigates hourly volumes. Finally, one study reports both crash frequencies and a case-control analysis (Yu & Abdel-Aty, 2013).

2.2.2 How well has the effect of traffic volume been studied?

Most of the studies on which the meta-analyses are based are from the United States, and some are from Asian countries (e.g. Korea, China). They are all based on data from motorways, with a focus on general crashes (not specific types). Three of the five original studies are from the United States, one from Canada and one from Italy. All but one of these, which is based on a principal arterial, are based on data from motorways. While several studies indicate that different functional forms describe the relationships between traffic volume and different crash types, this was not done in all studies, and findings were somewhat mixed.

It should be noted that the study designs of the reviewed studies (mostly cross-sectional, or case-control) identify associations between traffic volume and crash numbers. However, their results do not in and by itself reveal whether this relationship is causal or not, i.e. whether the number of vehicles causes a change in risk or crash frequency, or if the association is better explained by some other mechanism.

2.2.3 Transferability

From the reviewed studies it is not clear how (/if) the effect of traffic volume on crash counts differ between road types, countries, and crash types. While many recent studies investigate how traffic volume, in addition to other traffic flow characteristics, relate to crash risk, the contradictory results of the two meta-analyses indicate that the relationship between crash risk and real-time traffic volume could benefit from further research. Reviews note that the effect of traffic volume is likely to depend on weather conditions and other traffic characteristics (such as speed and density), which is not taken into account in all reviewed studies. More research might be needed to establish this.

2.3 DESCRIPTION OF ANALYSIS CARRIED OUT

Results of seven studies reviewed for traffic flow, of which two meta-analyses, are summarized below. Additionally, many studies with main focus on other risk factors (reviewed for other SafetyCube topics) are summarized briefly. More details on these studies and their results can be found in the supporting document.

2.3.1 Results from meta-analyses

Two meta-analyses were identified, both concerned with studies assessing real-time crash risk of different traffic characteristics (e.g. speed variation and occupancy), including traffic volume. One of the meta-analyses only reports one summary estimate for volume, measured downstream of the crash (and non-crash control case) (Xu et al., 2015), while the other also includes studies in which it was not specified which sensor was used (could be either upstream or downstream, or nearest) (Roshandel et al., 2015).

Table 1. Overview of summary estimates for traffic volume from meta-analyses.

Detector placement	Summary estimates	Effect on crash risk	
		↗	↘
All	1	1	
Upstream	2	1	1
Not distinguished	1	1	

No non-significant results were reported. The meta-analyses report contradictory results for upstream volume. There is some overlap between the primary studies on which the meta-analyses are based, but also a few differences between the meta-analyses, such as the number of studies included, and the criteria applied for including primary studies (see supporting document for details). It is, however, not clear what best explains the conflicting results.

Issues related to the type of study included in the meta-analyses are noted by Roshandel, Zheng, and Washington (2015): First, the time intervals chosen to measure traffic appears to be chosen arbitrarily in most cases, which might have an impact on the estimated results. Second, most studies do not validate their models, and those who do show inconsistent performance and high prediction errors. Third, as most studies are not guided by a theoretical approach relating traffic characteristics to crash occurrence, it is not clear what traffic states should be associated with increased risk, which might lead to data-mining approaches identifying spurious relationships.

A more general issue with the two meta-analyses is that neither clearly specifies what types of models the estimates on which they are based were taken from. More specifically, it is not clear to what extent the traffic volume estimates origin from models controlling for other traffic characteristics, or if this could be an issue in estimating (and interpreting) a summary estimate. As an example, one might imagine that an effect estimate for traffic volume *controlled for* speed and occupancy could differ form an estimate in a model without these variables. While it is evident that the primary studies control for different confounding factors and focus on different traffic characteristics, it is not made clear if the summary estimates are the effect of volume *controlled for* e.g. occupancy and speed variation or not, or to what degree this could affect the results. This also means that it is not clear if the results are the effect of traffic volume *given* i.e. speed or not.

2.3.2 Vote-count analysis

Among the five original studies reviewed, none used the same (or largely similar) analyses, outcomes, and traffic volume indicators, rendering a meta-analysis infeasible. The results are therefore presented in the form of a vote-count analysis, in which each estimate gets one vote on the effect of traffic volume. The estimates included are one per main listed condition in each study. In this vote-count analysis, a vote could take four different values:

- An increase in crash frequency that is less than proportional to the volume increase, indicating a *higher number of crashes* in total, but *lower risk* per road user (↗).
- An increase in crash frequency proportional to, or more than proportional to the volume increase (↗↗), indicating *increased frequency and increased risk*
- A non-significant relationship (-)
- A decrease in crash frequency (which would also correspond to lower risk) (↘)

However, no studies showed increased volumes to be associated with a net decrease in crash frequency. The majority of estimates are for crash frequencies, and one set of estimates is based on real-time crash risk.

Table 2. Effects of traffic volume on road safety by crash type and traffic volume measurement.

	Estimates	Results (n estimates)			Results (% of estimates)		
		↗	↗↗	-	↗	↗↗	-
All crashes*							
Total	**7**	**7**			**100%**		
AADT	5	**5**			100%		
Hourly	2	**2**			100%		
Multi-vehicle							
Total	**7**	**2**	**4**	**1**	**28 %**	**57%**	**14 %**
AADT	4	2	2		50 %	50 %	
Hourly	2		2			100 %	
Single-vehicle							
Total	**4**	**3**		**1**	**75 %**		**25 %**
AADT	2	1		1	50 %		50 %

*Note: * refers to model results where all crashes are considered jointly. MV and SV estimates outlined in table are not included in "all crashes". The level of traffic volume aggregation is not presented for categories with one estimate only. Percentages could sum to less than 100 due to rounding effects.*

For the impact of traffic volume on all crashes considered jointly, all studies report that as traffic volume increases, the total number of crashes increases as well, but that this increase is less than proportional to the traffic volume increase, which translates to lower risk per road user (coefficient estimates range from 0.25-0.62). One of the studies finding such a result is Lord and colleagues (2005) who also report that the numbers of single-vehicle crashes decline at increasing volumes, but that multi-vehicle crashes increase more than proportional to the volume increase (increased risk).

All studies that investigate crash frequency for SV and MV crashes separately find different relationships for multi- and single-vehicle crashes: SV crashes increase less than proportional to volume increase, but the results for MV crashes are more mixed. This is in part because Qin et al. (2004) report different results for different MV crashes: intersecting crashes are found to increase less than proportional to, opposite direction crashes increase proportional to, and MV crashes between oncoming vehicles increase more than proportional to volume increases.

There are a number of plausible reasons why the results would differ. First, differences in the level of aggregation at which traffic is measured could explain some between-study variation. For instance, Yu and Abdel-Aty find that increased AADT is related to a higher MV crash frequency, but unrelated to SV frequency. However, for a case-control analysis of real-time crash risk, volume is not related to MV crash risk, but a higher (downstream) volume increases the probability of SV crash risk. It may also be that the types of crashes considered or not considered (all/SV and MV; different types of MV), or actual differences in the investigated samples, for instance differences between countries, road types or other factors, could have contributed to the findings. While these explanations are not mutually exclusive, based on the reviewed studies it is not possible to say for certain which is most relevant.

One study finds that while heavy traffic volume increases the risk of crash involvement for all drivers, this effect is larger for females than for males, and also larger for young and older drivers than for middle-aged drivers (Abdel-Aty & Radwan, 2000).

2.3.3 Other findings

Results for the effect of traffic volume on road safety were also reported in studies reviewed for other SafetyCube risk factors. The results are presented in greater detail in the supporting document. The main findings are:

- In work zones, a higher AADT is associated with higher frequencies of both PDO and injury crashes. The same is found for crash rates (3 studies).
- A higher accumulated ADT over the construction period is related to a higher crash frequency, but crash frequencies increase at a decreasing rate (1 study)
- For ramp areas, a higher AADT both on the ramp and mainline is associated with an increased crash frequency (4 studies).
- A higher AADT is associated with increased crash severity in merging and diverging areas/exit ramp segments (3 studies).

5 studies with other main focus areas find less comparable results. Generally, most of the studies in which crash frequency is the outcome variable, higher volumes are associated with crash increases that are less than proportional to the volume increase.

2.4 CONCLUSION

Five primary studies and two meta-analyses were reviewed and summarized. The effect of traffic volume on crash frequency seems to be non-linear, with increased volume corresponding to more crashes, but lower risk. This means, for example, that if traffic volume increases from 5,000 to 10,000 vehicles per day, the number of crashes will not be doubled, but increase from, for example, 4 to 6. However, the results are somewhat inconsistent, and it remains unclear how traffic volume relates to real-time crash risk, and if differences in results are due to differences in studies areas, degree of aggregation, crash types considered or methodology. Thus, the effect of traffic volume on different types of crashes, as well as on different levels of crash severities, could benefit from more research. Additional results provided from studies dedicated to other risk factors mostly indicate that crash frequencies increase less than proportional to volume increases.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature search strategy

The databases Science Direct, TRID and Taylor & Francis were used to identify relevant studies for traffic volume. Due to paper titles not being sufficiently informative, abstracts of potentially relevant papers were screened during the search, and potentially relevant studies were retrieved for full-text screening.

In addition to this focused search, the work on other risk factors also returned estimates for traffic volumes, identified and coded by other SafetyCube partners for other primary topics. While providing relevant results, these studies are mainly focused on factors other than traffic volume, and the results of these 21 studies are dealt with under a separate heading at the end of this document.

3.1.2 Principles

Limitations/exclusions for search in all databases:

- Title-ABSTR-KEY
- Journal articles and reports
- 2000-2016
- English language

3.1.3 Search terms and hits

Database: Science Direct **Date:** 15th of March 2016

search no.	search terms / operators / combined queries	hits
#1	TITLE-ABSTR-KEY ("AADT" OR "annual average daily traffic" OR "traffic volume" OR "hourly volume") AND TITLE-ABSTR-KEY(road OR accident* OR crash* OR injur* OR incident* OR risk OR safety)	482

Database: TRID (trid.trb.org) **Date:** 17th of March 2016

search no.	search terms / operators / combined queries	hits
#1	(AADT OR "annual average daily traffic" OR "traffic volume" OR "hourly volume") AND (accident* OR crash* OR incident* OR injur* OR risk OR safety) [2000 onwards, only articles and reports, english only]	1407
#2	(accident* OR crash* OR incident* OR injur* OR risk OR safety) [+index terms AADT or traffic volume]	817

Database: Taylor & Francis **Date:** 17th of March 2016

search no.	search terms / operators / combined queries	hits
#1	(AADT OR "annual average daily traffic" OR "traffic volume" OR "hourly volume")AND (accident* OR risk OR safety OR crash* OR injur* OR incident*)	1467

3.1.4 Screening and eligibility

A total of 23 studies were obtained and full-text screened. The following elimination criteria was applied:

- Included in meta-analyses identified
- Results not compatible with coding (i.e. unusual analysis)
- No crash data

3.1.5 Screening and prioritizing coding

Among the studies remaining, a lower priority for coding was assigned to those who:

- Had a main topic other than traffic flow/volume
- Grouped AADT (loss of information)
- Lack of reporting of methodological detail made interpretation of results difficult

Finally, a higher priority was given to meta-analyses, and studies from European countries. In the end, seven of the studies with the highest priority were coded and reviewed.

3.2 LIST OF CODED STUDIES

Studies coded primarily for AADT

Abdel-Aty, M. A., & Radwan, A. E. (2000). Modeling traffic accident occurrence and involvement. Accident Analysis & Prevention, 32(5), 633–642. doi:10.1016/S0001-4575(99)00094-9

Caliendo, C., Guida, M., & Parisi, A. (2007). A crash-prediction model for multilane roads. Accident; Analysis and Prevention, 39(4), 657–70. doi:10.1016/j.aap.2006.10.012

Lord, D., Manar, A., & Vizioli, A. (2005). Modeling crash-flow-density and crash-flow-V/C ratio relationships for rural and urban freeway segments. Accident Analysis and Prevention, 37, 185-199. doi: 10.1016/j.aap.2004.07.003

Qin, X., Ivan, J. N., & Ravishanker, N. (2004). Selecting exposure measures in crash rate prediction for two-lane highway segments. Accident Analysis & Prevention, 36(2), 183–191. doi:10.1016/S0001-4575(02)00148-3

Roshandel, S., Zheng, Z., & Washington, S. (2015). Impact of real-time traffic characteristics on freeway crash occurrence: systematic review and meta-analysis. Accident; Analysis and Prevention, 79, 198–211. doi:10.1016/j.aap.2015.03.013

Xu, C., Wang, W., Liu, P., & Li, Z. (2015). Calibration of crash risk models on freeways with limited real-time traffic data using Bayesian meta-analysis and Bayesian inference approach. Accident; Analysis and Prevention, 85, 207–18. doi:10.1016/j.aap.2015.09.016

Yu, R., & Abdel-Aty, M. (2013). Multi-level Bayesian analyses for single- and multi-vehicle freeway crashes. Accident; Analysis and Prevention, 58, 97–105. doi:10.1016/j.aap.2013.04.025

Studies coded for other topics (not fully integrated in synopsis, see final part of this document for details)

Bared, J., Giering, G. L., & Warren, D. L. (1999). Safety evaluation of acceleration and deceleration lane lengths. *Institute of Transportation Engineers. ITE Journal*, *69*(5), 50.

Chen, E., & Tarko, A. (2012). *Analysis of Work Zone Crash Frequency with Focus on Police Enforcement.* Paper presented at the Transportation Research Board 91st Annual Meeting.

Chen, E., & Tarko, A. P. (2014). Modeling safety of highway work zones with random parameters and random effects models. *Analytic methods in accident research*, *1*, 86-95.

Chen, F., Ma, X., & Chen, S. (2014). Refined-scale panel data crash rate analysis using random-effects tobit model. *Accident Analysis & Prevention*, *73*, 323-332.

Chen, H., Lee, C., & Lin, P.-S. (2014). Investigation Motorcycle Safety at Exit Ramp Sections by Analyzing Historical Crash Data and Rider's Perception. *Journal of transportation technologies, 2014*.

Chen, H., Liu, P., Lu, J. J., & Behzadi, B. (2009). Evaluating the safety impacts of the number and arrangement of lanes on freeway exit ramps. *Accident Analysis & Prevention*, *41*(3), 543-551.

Chen, H., Zhou, H., Zhao, J., & Hsu, P. (2011). Safety performance evaluation of left-side off-ramps at freeway diverge areas. *Accident Analysis & Prevention*, *43*(3), 605-612.

Choi, J., Kim, S., Heo, T.-Y., & Lee, J. (2011). Safety effects of highway terrain types in vehicle crash model of major rural roads. *KSCE Journal of Civil Engineering, 15*(2), 405-412.

Daniel, J. R., & Maina, E. (2011). Relating Safety and Capacity on Urban Freeways. Procedia - Social and Behavioral Sciences, 16, 317–328.

Garnowski, M., & Manner, H. (2011). On factors related to car accidents on German Autobahn connectors. *Accident Analysis & Prevention, 43*(5), 1864-1871.

Khattak, A. J., Khattak, A. J., & Council, F. M. (2002). Effects of work zone presence on injury and non-injury crashes. *Accident Analysis & Prevention, 34*(1), 19-29.

Mergia, W. Y., Eustace, D., Chimba, D., & Qumsiyeh, M. (2013). Exploring factors contributing to injury severity at freeway merging and diverging locations in Ohio. *Accident Analysis & Prevention, 55*, 202-210.

Milton, J. C., Shankar, V. N., & Mannering, F. L. (2008). Highway accident severities and the mixed logit model: an exploratory empirical analysis. *Accident Analysis & Prevention, 40*(1), 260-266.

Montella, A., & Imbriani, L. L. (2015). Safety performance functions incorporating design consistency variables. *Accident Analysis & Prevention, 74*, 133-144.

Ozturk, O., Ozbay, K., Yang, H., & Bartin, B. (2013). *Crash frequency modeling for highway construction zones.* Paper presented at the Transportation Research Board 92nd Annual Meeting.

Rahman, M. M., Katan, L., & Tay, R. (2011). *Injury risks in collisions involving buses in Alberta.* Paper presented at the Transportation Research Board Annual Meeting, 90th, 2011, Washington, DC, USA.

Wang, Z., Cao, B., Deng, W., Zhang, Z., Lu, J. J., & Chen, H. (2011). Safety evaluation of truck-related crashes at freeway diverge areas. *Transportation Research Board*.

Wang, Z., Chen, H., & Lu, J. (2009). Exploring impacts of factors contributing to injury severity at freeway diverge areas. *Transportation Research Record: Journal of the Transportation Research Board*(2102), 43-52.

Wang, C., Quddus, M., & Ison, S. (2013b). A spatio-temporal analysis of the impact of congestion on traffic safety on major roads in the UK. Transportmetrica, 9935(July 2015), 1–25.

Wu, W.-q., Wang, W., Li, Z.-b., Liu, P., & Wang, Y. (2014). Application of generalized estimating equations for crash frequency modeling with temporal correlation. *Journal of Zhejiang University SCIENCE A, 15*(7), 529-539.

Yang, H., Ozbay, K., Ozturk, O., & Yildirimoglu, M. (2013). Modeling work zone crash frequency by quantifying measurement errors in work zone length. *Accident Analysis & Prevention, 55*, 192-201.

Studies screened full text, not coded based on elimination and/or prioritization criteria

Ayati, E., & Abbasi, E. (2011). Investigation on the role of traffic volume in accidents on urban highways. Journal of Safety Research, 42(3), 209–14. doi:10.1016/j.jsr.2011.03.006

Chen, C., & Xie, Y. (2016). Modeling the effects of AADT on predicting multiple-vehicle crashes at urban and suburban signalized intersections. Accident; Analysis and Prevention, 91, 72–83. doi:10.1016/j.aap.2016.02.016

Christoforou, Z., Cohen, S., & Karlaftis, M. G. (2012). Integrating Real-Time Traffic Data in Road Safety Analysis. Procedia - Social and Behavioral Sciences, 48, 2454–2463. doi:10.1016/j.sbspro.2012.06.1216

Haleem, K., Alluri, P., & Gan, A. (2015). Analyzing pedestrian crash injury severity at signalized and non-signalized locations. Accident; Analysis and Prevention, 81, 14–23. doi:10.1016/j.aap.2015.04.025

Jonsson, T., Ivan, J. N., & Zhang, C. (2007). Crash Prediction Models for Intersections on Rural Multilane Highways: Differences by Collision Type. Transportation Research Record, 2019, 91–98. doi:10.3141/2019-12

Karlaftis, M. G., & Golias, I. (2002). Effects of road geometry and traffic volumes on rural roadway accident rates. Accident Analysis & Prevention, 34(3), 357–365. doi:10.1016/S0001-4575(01)00033-1

Kononov, J., & Durso, C. (2012). Relationship Between Traffic Density, Speed, and Safety and Its Implications for Setting Variable Speed Limits on Freeways. Transportation Research Record: Journal of the Transportation Research Board, 2280, 1–9. doi:10.3141/2280-01

Kononov, J., Hersey, S., Reeves, D., & Allery, B. K. (2012). Relationship Between Freeway Flow Parameters and Safety and Its Implications for Hard Shoulder Running. Transportation Research Record: Journal of the Transportation Research Board, 2280(-1), 10–17. doi:10.3141/2280-02

Lee, C., Hellinga, B., & Saccomanno, F. (2003). Real-Time Crash Prediction Model for Application to Crash Prevention in Freeway Traffic. Transportation Research Record, 1840(03), 67–77. doi:10.3141/1840-08

Pande, A., & Abdel-Aty, M. (2009). A novel approach for analyzing severe crash patterns on multilane highways. Accident; Analysis and Prevention, 41(5), 985–94. doi:10.1016/j.aap.2009.06.003

Qin, X., Ivan, J. N., Ravishanker, N., Liu, J., & Tepas, D. (2006). Bayesian estimation of hourly exposure functions by crash type and time of day. Accident; Analysis and Prevention, 38(6), 1071–80. doi:10.1016/j.aap.2006.04.012

Roque, C., & Cardoso, J. L. (2014). Investigating the relationship between run-off-the-road crash frequency and traffic flow through different functional forms. Accident; Analysis and Prevention, 63, 121–32. doi:10.1016/j.aap.2013.10.034

Theofilatos, A., & Yannis, G. (2014). A review of the effect of traffic and weather characteristics on road safety. Accident; Analysis and Prevention, 72, 244–56. doi:10.1016/j.aap.2014.06.017

Xu, C., Liu, P., Wang, W., & Li, Z. (2012). Evaluation of the impacts of traffic states on crash risks on freeways. Accident; Analysis and Prevention, 47, 162–71. doi:10.1016/j.aap.2012.01.020

Xu, C., Wang, W., Liu, P., & Zhang, F. (2014). Development of a real-time crash risk prediction model incorporating the various crash mechanisms across different traffic states. Traffic Injury Prevention, 16(1), 28–35. doi:10.1080/15389588.2014.909036

Zheng, Z., Ahn, S., & Monsere, C. M. (2010). Impact of traffic oscillations on freeway crash occurrences. Accident; Analysis and Prevention, 42(2), 626–36. doi:10.1016/j.aap.2009.10.009

3.3 DESCRIPTIONS OF CODED STUDIES AND SAMPLING FRAMES

3.3.1 Meta-analyses

Two studies were coded in which a meta-analysis was carried out for the effect of traffic volume on road safety. Both meta-analyses were based on studies with disaggregated traffic data (mostly 5-minute intervals), and two primary studies were included in both meta-analyses. Table 3 lists main differences between the meta-analyses. Both meta-analyses included only studies that considered all crashes jointly, and excluded studies with very aggregated data.

Table 3. Comparison of (traffic volume aspects of) meta-analyses.

Characteristics	Xu et al, 2015	Roshandel et al, 2015
Studies (estimates)	7 (9)	6(6)
Studies included if	Effects are OR/ log(OR); 5-min time intervals; traffic flow at same location with respect to crash site (up- or downstream)	Not ramps only
Traffic data, time intervals	Loop detector data with 5 minute intervals.	Loop detector and trajectory data, several intervals.
Loop detector placement	Upstream (9)	Upstream (4), not distinguished (2)
Meta-analysis	Bayesian with fixed effects, random effects, and meta-regression (freeway as explanatory).	Inverse variance meta-analysis with random effects for "all", unclear if fixed or random effects are used for upstream and not distinguished-estimates.
Effect on risk per detector placement		
all	-	↗*
upstream	↗	↘
not distinguished	-	↗*

Note: * The increments are minor, OR 1.001. The table outlines the numbers of studies and estimates on traffic volume. The total number of studies and estimates included is larger in both instances, as several traffic characteristics are investigated.

3.3.2 Original studies

Table 4 describes the sampling frames, analyses and main results of the original studies coded for the traffic volume risk factor.

Table 4. Overview of methodology and main results for original studies coded for traffic volume.

Author(s)	Area, sample.	Traffic flow	Design, analysis	Outcome	Crashes	Control variables	Result	Explanation
Abdel-Aty & Radwan, 2000, USA	Principal arterial, motorway in Central Florida. 3 years of crash data (1992-1994). 566 segments.	AADT per lane	Observational, negative binomial	Crash frequency	All	section length; degree of horizontal curve; shoulder width; median width; lane width/number of lanes; urban	↗	AADT increases risk, more so than other parameters investigated.
Qin et al., 2004, USA	Two-lane rural highways, 29800 segments. 4 years of data, each year analysed separately (similar results for all years).	AADT both directions	Observational, zero-inflated-poisson	Crash frequency	SV	segment length; shoulder width; lane width; speed limit	↗	Single vehicle crashes increase, but become less likely at increasing AADT.
					MV-intersecting		↗	Become less likely at increasing AADT
					MV-opposite direction		↗↗	Increase proportionally with AADT
					MV-oncoming		↗↗	Increase more than proportional to AADT
Caliendo et al., 2007, Italy	Four-lane Italian motorway, 46,6 km. 5 years of crash data (1999-2003).	AADT/1000	Observational, negative binomial	Crash frequency	All; tangent	section length; surface status; presence of junctions; year	↗	Higher AADT related to increased crash frequency, less than proportional to volume increase.
					All – curve		↗	
					Severe; fatal - tangent		↗	
					Severe; fatal - curve		↗	
Yu & Abdel-Aty, 2013, USA	Mountainous freeway (15 miles) Colorado. Aggregate (5 years)	AADT	Observational. Bayesian bivariate poisson-lognormal model	Crash frequency	MV	Degree of curvature; curve length ratio (to section length); number of lanes; segment length; median width	↗↗	Higher AADT increases probability of MV crash occurrence
				Crash frequency	SV		-	No impact on the probability of SV crash occurrence
	Mountainous freeway (15	Volume at 5-	Case-control,	Crash risk	MV		-	MV: volume ns.

	miles), Colorado. Disaggregate (1 year). 109 MV and 150 SV, 4 times as many (matched) controls.	minute intervals at detectors up- and downstream	Bayesian logistic regression, seasonal random parameters					
			Case-control, Bayesian logistic regression, seasonal random parameters	Crash risk	SV	SD of occupancy; average speed; season	↗	SV: higher sum volume downstream is associated with increased risk (other detectors presumably ns)
Lord et al., 2005, Canada	Rural motorway (40 km). 5 years (1994-1998).	Hourly traffic volume estimates based on loop detector data, per direction	Observational, generalized negative binomial	Crash frequency (per time, section and direction)	All	-	↗	Crashes increase at a decreasing rate.
					Severe + fatal		↗	Crashes increase at a decreasing rate
					SV		↗	Crashes increase at a decreasing rate
					MV		↗↗	Increase in nearly linear manner with flow
	Urban motorway (5 km). 5 years (1994-1998).				All		↗	Crashes increase at a decreasing rate
					MV		↗↗	Increase in nearly linear manner with flow

Lord et al (2005) also finds that traffic volume alone might not properly characterize crashes on freeways. They develop a different set of models that also include density, and find that for both all and single crashes, crash frequencies initially increase, and then decrease as density increases. However, MV-crashes increase with increasing density, and the functional form is different for urban and rural areas.

3.4 TRAFFIC VOLUME IN DIFFERENT SETTINGS

This section is concerned with AADT estimates from studies with a main focus on different risk factors. These studies have been coded by other SafetyCube partners and are, as mentioned in the methodology section, not identified by the literature search for AADT, but from searches on other risk factors. These AADT results have been categorized as follows: a) studies on work zones, b) studies on ramps, merging and diverging areas, and c) other studies. The results and information provided in this section is based on the coding work of partners responsible for coding of the respective studies.

It should be noted that the study designs from which these results originate (mostly cross-sectional, and at times with time-series models or before-after design) identify associations between AADT and crash occurrence or crash severity. However, the information provided below does not in and by itself reveal whether this relationship is causal or not, i.e. whether traffic volume causes increased crash frequency/severity, or if this association is due to some other mechanism.

3.4.1 Traffic volume in work zones

Five studies on the effect of work zones on road safety provided estimates for the role of traffic volume. These results are presented in Table 5. The three studies investigating AADT in relation to work zones find that road safety deteriorates with increasing AADT, both for injury crashes and property damage only crashes. The studies of Chen and Tarko (2011; 2013) are based on the same dataset, and find that the crash frequency increases with the total number of vehicles passing through the work zone over the entire construction period, but at a decreasing rate. The authors note that "it may also mean that longer work zones with higher traffic volume exhibit lower crash rates (per unit length or unit volume) than shorter or less busy work zones".

Table 5. Effects of traffic volume on road safety in work zones.

Author(s), year, country	Sampling frame	Outcome, analysis	Traffic volume	Crash severity	Effect on outcome	Control variables
Chen & Tarko, 2013, USA	Indiana, 2009, 72 Work zones, several road types, n 547 observations	Crash frequency, fixed parameters negative binomial model with random effects, and with random parameters	Total ADT (accumulated over entire construction period	All	↘	Work zone length, left shoulder width; right-of-way- width; urban land development fraction; park lane fraction; detour sign; lane shift; lane split; restricted to one lane per direction; multilane with/without system interchange; low/high construction intensity; summer; winter per area
Chen & Tarko, 2011, USA		Crash frequency, random effect negative binomial model	Total ADT (accumulated over entire construction period	All	↘	Work zone length; fractions in urban area/road with full access control/road with parking lane prior to construction/collector road; avg left shoulder width; right of way width; lane shift; lane split; winter; summer; concrete pavement in poor condition; work intensity; police enforcement
Khattak et al., 2002, USA	California, 1992-1993, work zones and non-work zones n 144	Crash rate, negative binomial model	Ln(AADT)	PDO, injury	↗	Work zone presence; work zone duration; work zone length; urban indicator; injury indicator
	California, work zones, 1992-1993, n 36 work zones	Crash rate, negative binomial model	Ln(AADT)	PDO	↗	work zone duration; work zone length; urban indicator
				Injury	↗	

Ozturk et al, 2013, USA	New Jersery 2004-2010. N=950	Crash frequency, negative binomial model	Ln(AADT)	PDO	↗	work zone length, night, speed, n operating lanes, n closed lanes, speed limit, road class, n ramps, n intersection, duration of work zone
				Injury	↗	
Yang et al., 2013, USA	New jersey state, 7 years, (2004-2010), 60 work zones.	Crash frequency, full Bayesian negative binomial models	Ln(AADT)	PDO	↗	light condition;speed limit;road system;dropped lanes;aadt;number of lanes; direction; season; hours
				Injury	↗	as above + work zone length

3.4.2 Ramps, merging and diverging areas

Nine studies coded primarily for the risk related to ramps, merging or diverging areas provide estimates for the effect of traffic volume on road safety in these areas. The sampling frames of these studies are presented in Table 6, and the results are summarized in Table 7.

Table 6. Sampling frames and analyses of studies on ramps, merging and diverging areas.

Author(s), year, country	Sampling frame	Crash type/severity	Analysis	Control variables
Bared J., Giering G., Warren D., 1999, USA	Sample of interstate highways in Washington State. Data from 1993-1995, n 1452, all severities. Mainline and ramp flows separately.	Mainline	Negative binomial	ramp length; AADT on ramp; AADT on the mainline; ramp type; rural area
		Ramp		
Chen et al., 2009, USA	Freeway diverge areas, Florida, 2004-2006, n=7872. Separate estimates for one- and two-lane exit ramps.	Ramp (exit)	Negative binomial	deceleration lane length; AADT in the mainline/ramp; shoulder width; speed limit
		Mainline		
Chen et al., 2011, USA	Freeway diverge areas, n=60, 4 years, observational, Florida.	Mainline	Negative binomial	deceleration lane length; ramp length; AADT on ramp/mainline segment; ramp type
		Ramp		
Chen et al., 2014, USA	Motorcycle crashes, 2005-2010, Florida state, n 573.	Ramp	Negative binomial	ramp length, directional exit, loop exit, outer connection exit, ramp speed limit
Garnowski, Manner, 2011, Germany	Germany, Dusseldorf, 197 ramps and n 3048.	Ramp	Negative binomial, random parameters	truck percentage; deflection angle; curve gets steeper; length deceleration lane; lane width; position steepest curve
Mergia et al., 2013. USA	Ohio, 2006-2009, merging and diverging areas, motorway.	Diverging areas	Generalized ordinal logit	Adverse weather; adverse road condition; age;gender;collision type; n mainline lanes; n ramp lanes; alcohol related; speed related; lane-ramp configuration type [not all are used for all severity comparisons]
		Merging areas		
Wang et al., 2009, USA	2003-2006, crashes on selected ramps in state of Florida. N=10946.	Freeway diverge areas; exit ramp segments	Ordered probit	deceleration lane length; AADT on the mainline; ramp length; ramp length; curve/no; grade/no; shoulder width; speed on the mainline; number of lanes on the mainline; surface; landtype; peak hour; alcohol; heavy vehicle/not; time; crash type; barrier
Wang et al., 2011, USA	diverge areas, truck-crashes. N= 4630. 2005-2008.	Mainline	Ordered probit	shoulder width; median width; deceleration lane length; number of lanes; ramp type; AADT of trucks in the mainline/exiting AADT
		Exiting		
Wu et al., 2014, China	Motorway ramp crashes over 4 years.	Mainline	Generalised Linear Model for four year average	bad weather, temporal correlation
		Ramp		
		Mainline	Generalised	bad weather, temporal correlation

		Ramp	Linear Model for annual data	

Generally, the studies indicate that increased AADT in ramp areas, on ramps and in the mainline nearby the ramp is related to increased crash occurrence. A higher AADT in merging and diverging areas also appear to affect crash severity adversely. The evidence for different road users is limited, and should thus be considered with caution. Nonetheless, the results indicate that this is also the case for motorcycle crashes, while the severity of truck crashes is worsened by a higher truck AADT in the mainline and unaffected by the exiting AADT.

Table 7. Effects of AADT on road safety from studies on ramps, merging and diverging areas.

Author(s), year, country	AADT modelled as	Where	Outcome	Effect on outcome
Bared, Giering, & Warren, 1999, USA	AADT	Mainline	Crash count	-
	AADT	Ramp	Crash count	↗
Chen et al., 2009, USA	AADT	Ramp (exit)	Crash count one-lane ramp	↗
			Crash count two-lane ramp	↗
		Mainline	Crash count one-lane ramp	↗
			Crash count two-lane ramp	↗
Chen et al., 2011, USA	Ln(AADT in thousand)	Mainline	Crash count (per year)	↗
		Ramp	Crash count (per year)	↗
Chen et al., 2014, USA	AADT (in thousands)	Ramp	Crash count, motorcycle crashes	↗
Garnowski & Manner, 2011, Germany	Ln(AADT passenger cars)	Ramp	Crash count	↗
Mergia et al., 2013, USA	AADT	Diverging areas	Crash severity (fatal vs non-fatal)	↗
		Merging areas		↗
Wang et al., 2009, USA	AADT	Freeway diverge areas; exit ramp segments	Crash severity	↗
Wang et al. 2011, USA	AADT (in thousand)	Exiting	Crash severity, truck crashes	-
	AADT trucks (in thousand)	Mainline	Crash severity, truck crashes	↗
Wu et al., 2014, China	ln(AADT)	Mainline	Crash count on ramp, 4 year average	-
		Ramp		-
		Mainline	Crash count on ramp, annual	↗
		Ramp		↗

Note: for crash frequency outcomes, ↗ indicates and increase in crashes, corresponding to a worsening of road safety. Similarly, the upward arrow reflects a higher probability of more severe crashes. – indicates a non-significant effect.

The 4 studies examining the importance of AADT on road safety without focusing on specific road users all find that crash frequency increases with increasing ramp AADT. One of these studies finds this only on an annual level analysis and not for 4 years of data aggregated (Wu et al., 2014), while another finds this tendency for both one- and two-lane exit ramps. 3 of the 4 studies find a higher mainline AADT to be associated with increased crash frequency, while one finds it not to be statistically significant.

3.4.3 Other studies

Five remaining studies with other main focus areas have also been coded. They are summarized in Table 8.

Table 8. Overview of sampling frames and main results of other studies.

Author(s), year, country	Sampling frame, [main focus of study]	Traffic volume	Outcome	Analysis	Effect on outcome	Control variables
Choi et al., 2011, Korea	Case-control, 2002-2003, rural national roads. [Highway terrain types]	AADT	Crash severity (PDO, minor, serious, fatal)	Ordinal logistic regression	↗	Travel speed; shoulder width; median and terrain type
Milton et al., 2008, USA	Highway, state of Washington, observational longitudinal, 1990-1994 [Injury severity distributions.]	AADT general	Crash severity (PDO, possible injury; injury)	Mixed logit	↘	Average annual snowfall; AADT truck; Number of interchanges per mile
		AADT trucks			↘	Pavement friction; Percentage of trucks
Chen et al., 2014, USA	Segment of Colorado motorway. 1 year. [Predicting hourly crash rates]	Hourly volume	Crash rate daytime	Random effects tobit models	↗	Low speed limit; speed gap; % trucks; visibility; November; weekend; n enter ramps, n lanes, segment length; curvature, shoulder width; long remaining service life of rutting; wet road surface; snow;
			Crash rate night-time		↗	
Rahman et al., 2011, Canada	Alberta, single bus collisions on highways, n 109, 2000-2007, [Bus crashes]	Ln(AADT)	Crash severity (injury, PDO)	Binary logistic regression	↗	Type of collision; gender; season; weather; light condition
Montella & Ibramini, 2015, Italy	Motorway section Naples area, 2007-2011 [Highway design]	Ln(AADT)	Crash frequency	Generalised linear model, negative binomial error structure	↗	Dispersion, constant, design consistencies, yearly effects
Wang et al., 2013, UK	Major roads and motorways, London area, 2007-2013 [Congestion]	Ln(AADT)	Crash frequency, KSI crashes	Bayesian spatial model	↗	Congestion (delay); maximum gradient; number of lanes; speed limit; motorway; year; spatial correlation
			Crash frequency, minor injury crashes	Bayesian spatial model	↗	
Daniel & Maina, 2011, USA	Urban and rural, freeways and arterials, New Jersey, 1 year [Capacity]	AADT	Crash frequency	Negative binomial	↗	V/c-ratio; section length; % trucks: speed limit; number of lanes; lane width; shoulder width; ramp density.

Crash rates are found to be higher both at daytime and night time when the hourly volume is higher (Chen et al., 2014). The effect of traffic volume on crash severity varies between studies: Choi et al.

(2011) finds a higher AADT to be associated with more severe crashes, while Milton et al (2008) find the opposite. Rahman et al. (2011) find single bus crashes more likely to be injury than PDO when AADT is high.

Daniel & Maina (2011) find crashes to increase less than proportional to traffic volume

The study of Montella & Ibramini (2015) finds a higher AADT to be negative for road safety under a wide range of conditions, and find that, in both curves and tangents, a higher AADT is related to an increased crash rate for the following types of crashes: single-vehicle run-off-the-road, other single vehicle, multi vehicle, daytime crashes, night-time crashes, non-rainy weather crashes, rainy weather crashes, dry pavement crashes, wet pavement crashes, property damage only, slight injury, and severe injury (including fatal), as well as all crashes considered jointly.

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Synopsis 2: Congestion as a risk factor

1 Summary

Hesjevoll, I.S. August 2016

COLOUR CODE: GREY

Explanation: Studies on congestion find mixed results on how this affects road safety. The effects might differ based on the crash types and/or congestion indicators considered.

KEYWORDS

Congestion; queue; delay; v/c-ratio; volume-to-capacity ratio; capacity; travel time; density; speed; traffic flow

1.1 ABSTRACT

Congestion refers to a traffic state with slow-moving or still-standing traffic, which could occur due to road, traffic, or weather situations. Congestion might affect road safety due to decreased speed (less severe crashes), high degrees of speed variation within and between lanes increasing the complexity of driving (more crashes), or by creating stress (detrimental for driver behaviour). Most studies define congestion based on travel time, speed, or traffic density. Studies using a density-based definition of congestion (volume/capacity-ratio) report congestion to be associated with fewer crashes in total, but find different tendencies for single-vehicle and multi-vehicle crashes. Studies defining congestion by increased travel time or decreased speed generally find congestion to be associated with a higher number of crashes (including injury crashes), but this is not reported under all conditions. Due to a low number of relatively dissimilar studies, the effect and potential transferability is uncertain. Most reviewed studies are from the United States, and all are based on motorways, which could explain the somewhat surprising result that injury accidents are not found to decrease in congested traffic states. No distinctions are made between different road users.

1.2 BACKGROUND

1.2.1 What is congestion, and how is it measured?

Congestion as defined by slow-moving or still-standing traffic, could occur due to a number of reasons. On some roads, congestion is recurrent, often due to oversaturation. Other roads are not prone to recurrent congestion, but non-recurrent congestion might occur due to unexpected events or incidents (see synopsis on crashes contributing to further crash occurrences). Definitions and measurements of congestion vary, the following three types are the most common: The first is based on *speed*, e.g. the actual speed versus the free flow speed. The second is based on travel time (e.g. a ratio of actual travel time to the time required to make the same trip at free-flow speed), and the third is based on *density* (vehicles per distance unit), often taking road capacity into account (volume-to-capacity ratio, or V/C-ratio). In addition, some studies differentiate congested and non-congested traffic states based on combinations of speed or speed variation and traffic volume or occupancy.

1.2.2 How does congestion affect road safety?

There does not seem to be consensus on how congestion affects road safety, but several plausible mechanisms have been proposed. First, it may be that a lower average speed has a beneficial effect on crash severity. On the other hand, speed variation in and between lanes might remain high even in congested traffic states, increasing the complexity of driving (e.g. more speed adjustments, shorter reaction time, more lane-changing behaviour). Additionally, congestion could increase stress, causing more aggressive driving behaviour such as passing in the shoulder, tailgating and honking/yelling, which could be detrimental for road safety.

1.2.3 What road safety outcomes are affected by congestion?

The majority of the reviewed studies focus on the impact of congestion on crash counts. Some consider the frequencies of different types of crashes (single-vehicle and multi-vehicle) or frequencies of different crash severities separately, and investigate whether congestion relates differently to different types of crashes, or which crash types are more common in congested states. Other studies consider all crashes jointly. Few studies use crash severity as an outcome variable.

1.2.4 How is the effect of congestion on road safety studied?

The reviewed studies are observational, cross-sectional or time-series studies, investigating associations between crash counts/rates/risk/severities and the degree of congestion. There are studies based on both aggregated and disaggregate (real-time) traffic data, but the majority address associations between average congestion and crash occurrence. All studies are based on data from motorways or other major roads.

1.3 OVERVIEW OF RESULTS

1.3.1 Main results

Seven studies were reviewed, and their results are mixed: Some find congestion to be associated with increases in crashes, other find decreases or no associations. The main tendencies are:

- Traffic density (Vehicle-to-capacity ratio) relates differently to the numbers of multi-vehicle and single-vehicle crashes: A higher v/c ratio is associated with fewer crashes when all crashes are considered jointly, and also single-vehicle crashes are found to be less frequent in dense traffic flows. Results for multi-vehicle crashes are inconsistent, they might increase or not be affected.
- Delay, or lower speed, is associated with higher crash frequencies in most cases, but not necessarily for all crash types and all times of the day. Findings are somewhat inconsistent.
- One study indicates that congestion is associated with less severe crashes if the entire road is congested, while congestion in one lane only is not related to crash severity.

1.3.2 Transferability

Among the seven reviewed studies, 5 are from the United States, and the remaining two from Canada and the UK. All studies investigate congestion on motorways or other major roads (but both urban and rural areas), and none focus on different road users. It is not clear whether results are transferable to different road types or countries. The effect of congestion on road safety might depend on how prevalent/common congestion is on a given road at a given time of day (i.e. whether road users are expecting and experienced with congestion), as well as factors such as speed/speed limit, road user composition (share of PTWs) and road design.

1.3.3 Notes on analysis methods

A limited amount of relevant studies was identified, and the study quality is inconsistent, with some studies controlling for few potentially confounding factors. The use of aggregate measurements for congestion in several studies could have contributed to biased results, and it is not clear how v/c-ratio relates to time- or speed-based congestion measures. More research is needed to establish the effect of congestion for different crash types in different contexts.

2 Scientific overview

2.1 LITERATURE REVIEW

2.1.1 On congestion indicators

Congestion measurements seem to fall into three main categories; based on density, on speed or on travel time. Two studies report testing different congestion measurements. Shi and colleagues (2016) found similar results for occupancy and the Congestion Index on which their main results are based (the congestion index is speed based, see table 1), and Wang et al. (2013) based their analysis on delay, but reported that in testing the Congestion Index, they arrived at similar results. This seems to indicate that one might expect measurements based on speed and travel time to yield similar results.

The reviewed studies that are based on density use volume-to-capacity-ratio (v/c-ratio); the number of vehicles passing a road section divided by road capacity. V/c-ratio is a measure from the Highway Capacity Manual (2001), where thresholds of v/c-ratio map onto different "levels of service", some of which are classified as congested traffic states. In the reviewed studies, v/c-ratio is modelled as a continuous variable.

If a defining trait of congestion is reduced speed, it could be argued that density-based measurements for congestion, such as v/c-ratio, is best understood as a proxy for congestion: Wang, Quddus and Ison (2009) note that the relationship between congestion levels and density is not clear, and that increases in congestion will probably not be proportional to density increases.

Regardless, the relationships between these measurements is not quite clear (for an overview of the theoretical relationship between density, flow, and speed, and a review of relevant research, see e.g. Wang, Quddus, & Ison (2013), and while one might expect similar results from studies using delay- and speed-based measurements, it is not clear if the same consistency should be expected with studies measuring v/c-ratio.

2.1.2 Mechanisms

The studies reviewed for this and related risk factor topics suggest various ways in which congestion could impact on road safety. Some of the results reported in reviewed studies indicate that speed variation, which characterises congested traffic, could contribute to increased crash risk in congested traffic states. While the average speed might be lower in congested traffic states than otherwise, the speed variation could still be high both within and between lanes. This could contribute to more frequent crashes as it increases the complexity of driving (e.g. more frequent speed adjustments, more lane changing behaviour).

In a recent review and meta-analysis of real-time traffic characteristics related to crash risk, based mainly on case-control studies conducted on motorways, Roshandel, Zheng, and Washington (2015) found that a higher coefficient of variation of speed (the standard deviation of speed divided by average speed) downstream was associated with increased risk of crash occurrence. In a review on the literature on the relationship between speed dispersion and road safety, Elvik (2014), too, found that speed dispersion is associated with increased crash risk. Shi et al. (2016) report that both congestion (speed-based), and speed variation are related to higher numbers of damage only and slight/severe/fatal injury crashes, especially during peak-hours.

This is in accordance with other reviewed studies that report that not only congestion, but also the transition from congestion to free flow (or vice versa), could have detrimental effects on road safety: Zheng (2012) found that both congestion and transition (characterized by variable occupancy and variable speed) is associated with increased crash risk. Golob and colleagues (2008) found that while congestion is generally related to a higher probability of crashes being property damage only (rather than injury crashes), this is no longer the case if the traffic flows are unstable, i.e. transitioning between free flow and congested states.

2.1.3 Crash data

This crash scenario analysis was conducted using cases from the German In-Depth Accident Study (GIDAS) database. All accidents were considered which were ready for analysis and which were collected in the years 2007 to 2015. In total, records from 14.398 accidents which occurred in the regions of Hannover and Dresden were analysed. The GIDAS database details those accidents which occurred on a public road where at least one person was injured. The accidents are collected according to a statistical sampling process to ensure a high level of representativeness of the actual accident situation in the sample regions. The data collection is conducted using the "on the scene" approach where all factors which were present at a crash are recorded. This does not mean that the recorded factor was a contributory factor towards the crash. For the current analysis all crashes where congestion was listed as present at the crash scene were compared to all crashes where congestion was not present at the crash scene. Note that, the risk factor is identified in relation to the involved party who was considered most at fault. Considering all crashes jointly, 282 (i.e. 2 %) occurred in congestion. However, when the share of crashes occurring in congestion is considered by road type, it varies from 0 to 12 %. As illustrated in figure 1, the percentage of crashes occurring in congestion is notably higher on motorways than on other road types. However, this might simply reflect that motorways are more prone to congestion than other road types, and does not indicate whether or not congestion contributes to more crashes on motorways. Furthermore, these patterns might differ between countries.

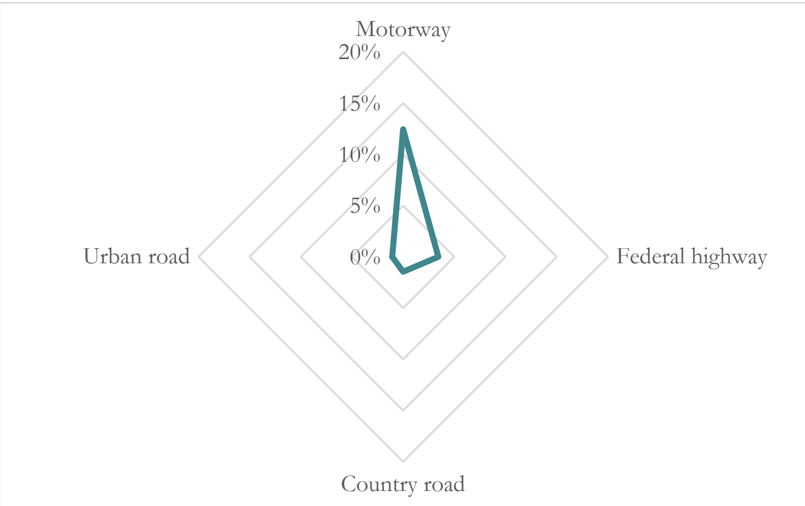


Figure 1. Percentage of crashes that occurred in congestion per road type.

1.1 DESCRIPTION OF STUDIES

1.1.1 How is the effect of congestion studied?

In the present overview, seven studies are reviewed. They are all recent (published 2000 or later), and most employ cross-sectional, observational designs using multivariate analyses to investigate the relationship between congestion and crash numbers/severities/risk. Some employ time series models. A detailed overview of sampling frames, congestion indicators, and methodology of the reviewed studies can be found in the supporting document. In short, five studies are based on U.S. data, while the remaining two are from the UK and Canada. All focus on data from motorways and/or other major roads. Three studies investigate volume/capacity ratios (Lord et al., 2005; Ivan et al., 2000; Daniel & Maina, 2011), two are based on speed/delay (Shi et al., 2016; Wang et al., 2013), while the remaining two define congestion based on combinations of speed and other traffic flow characteristics such as occupancy (Golob et al., 2008; Zheng, 2012).

Regarding the methodology, four studies use crash frequencies as the outcome variable (Lord et al., 2005; Shi et al., 2016; Wang et al., 2013; Dalien & Maina, 2011), in some cases separately for different crash severities, one is focused on crash rates (Ivan et al., 2000), one on crash risk (Zheng et al., 2012), and one on crash severity (Golob et al., 2008). The level of aggregation at which congestion is analysed varies between studies, as does the number of confounding factors controlled for.

2.1.4 How well has the effect of congestion been studied?

All studies are conducted on motorways, or motorways and other major roads, and none investigate the effect of congestion on road safety for different road users. Studies on different road types are lacking, and more research is needed to disentangle the effects of different measurements, contexts, and countries. Only one study uses crash severities as an outcome variable, and the effect of congestion on different crash types remains is unclear.

2.1.5 Transferability

Since all studies are conducted on motorways or other major road, the results are probably not transferable to other road types. Most studies are conducted in the United States, and the degree to which the effect of congestion on road safety varies between countries remains unknown. It may also be that the effect of congestion on road safety depends on whether the area in question is prone to recurrent congestion or not, the speed/speed limit or geometric features of the road environment.

2.2 ANALYSIS OF RESULTS

Among the seven reviewed studies, three used the same indicator of congestion (v/c-ratio). Due to differences in model architecture and variables included in the models, these studies were not considered sufficiently similar to calculate a summary estimate by means of a meta-analysis. The results of the three studies measuring congestion as v/c-ratio are summarized in a vote-count analysis. In a vote-count analysis, each estimate gets one vote on the effect of congestion on crash occurrence. The remaining studies were too heterogeneous to allow for direct comparison, and their main findings are summarized in

Table 2.

2.2.1 Vote-count analysis: V/C-ratio

A vote can take three different values: An increase in crash occurrence (↗), a decrease in crash occurrence (↘), or no significant difference (-). These vote-counts are differentiated with respect to the crash types used as dependent variables: Among the three studies addressing the relationship between vehicle-to-capacity ratio (v/c ratio) and crash occurrence, two of them analysed single-vehicle and multi-vehicle crashes separately (Lord et al., 2005; Ivan et al., 2000). One of these studies also analysed all crashes jointly, while the third study made no distinctions between crash types (Daniel & Maina, 2011). The estimates considered in the vote count analysis is one per study per type of crash . So while one study estimated separate models for urban and rural areas (Lord et al., 2005), the results of this study is counted as one vote per category, since the main result was similar for urban and rural areas.

For the two studies distinguishing between single-vehicle and multi-vehicle crashes, one has crash rate as an outcome variable (Ivan et al., 2000), and the other investigates crash frequency (Lord et al., 2005). The study results indicate that a higher v/c ratio is associated with fewer single-vehicle crashes, and also a decrease in all crashes. Regarding multi-vehicle crashes, it remains unclear whether a higher v/c ratio is unrelated to their frequency/rate of occurrence or associated with increased frequency/rate of occurrence.

Table 1. Results crash occurrence by crash type.

Crash type	Tested in studies	Result (number of studies)			Result (% of studies)	
		↗	-	↘	↗	↘
Single-vehicle	2			2	0%	100%
Multi-vehicle	2	1	1		50%	0 %
All	2			2	0%	100%

The relationships identified between v/c-ratio and single-vehicle crashes were found to have somewhat different functional forms in the two studies investigating this. Lord et al. (2005) found that the number of SV crashes increases as the V/C- ratio increases from 0 to 0,2, and decreases with further increases of the v/c-ratio. Ivan et al. (2000) found a negative-exponential relationship, where the crash rate was highest at low v/c-ratio, drops sharply, and then levels off.

While Lord and colleagues (2005) found a nearly linear relationship between increasing v/c-ratio and multi-vehicle crashes, Ivan and colleagues found no association, which they suggest could be due to the v/c-ratio only relates to intensity of traffic on the main road, not conflicts between intersecting roads. Lord and colleagues note that the area studied is not prone to recurrent congestion. Thus, it is not clear whether the differences in results are best explained by differences in outcome variables, study samples/areas or other factors.

2.2.2 Congestion indicators based on speed or travel time

The remaining studies differ too much in congestion indicators and outcome variables for their results to be directly compared. Their main findings are summarized in table 4.

Table 2. Main results of studies in which congestion is defined by speed or travel time.

Author(s), year, country	Congestion indicator (short)	Outcome	Crash type(s)		Effect on outcome	Explanation
Golob et al., 2008, USA	PCA-based, separate indicators for outer and inner lanes	Severity	PDO vs injury		↘	If the entire road is congested, crashes are more likely to be PDO, rather than injury. Congestion in the curb lane only has little effect on crash severity
Shi et al., 2016, USA	Congestion index, speed based	Crash frequency	All	peak	↗	Congestion (and speed variation) related to increased crash frequency during peak hours, but not in non-peak hours.
				non-peak	-	
			PDO	peak	↗	
				non-peak	-	
			KABC*	peak	↗	
				non-peak	-	
Wang et al., 2013, UK	Travel time delay	Crash frequency	Slight/PDO		-	Delay is associated with increases in KSI crashes, but not slight injury crashes
			KSI		↗	
Zheng, 2012, USA	Free flow, Transition, Congestion	Crash risk	All		↗	Congestion (and to a lesser degree transition) increases the odds of crash occurrence.

Note: *KABC refers to possible injury, slight injury, severe injury and fatal injury crashes.

All studies indicate that congestion is associated with increased crash occurrence, although this might not apply to all severities and/or times of day. Given that congestion is defined by decreased speed, which for each crash could mean reduced impact and severity, the fact that severe crashes increase in congestion might at first seem counter-intuitive. However, all studies are conducted on motorways, at which speeds could be high even under congested conditions. This may explain why some studies find severe crashes to increase in congestion. Furthermore, the majority of these studies are concerned with how the average degree of congestion relates to crash counts, which does not correspond to the traffic conditions directly prior to crash occurrence.

Wang et al. (2013) also found that if considering extreme levels of traffic congestion, where vehicles move very slowly, there may be a U-shaped relationship between congestion and the number of KSI crashes: At very high levels of congestion, the number of KSI crashes decreases. However, this degree of congestion was observed very rarely in their dataset, and their general conclusion remains that a 1% increase in traffic delay per kilometre would increase KSI crashes by about 0.1%.

Shi et al. (2016) find congestion to be detrimental for road safety during peak-hours, but that it is not relevant during non-peak hours. However, as noted by the authors, this finding could be explained by there not being any congestion in non-peak hours in the dataset (low readings and little variation).

Zheng (2012) reports limited information about the data and analysis, and the study controls for no potentially confounding variables. It is uncertain to which degree these results are generalizable.

2.2.3 Issues and limitations

In most studies, the congestion indicators are estimates, and often average estimates for longer periods of time or geographical areas - not the actual traffic conditions before the occurrence of the crash(es). This could introduce bias to the results, both because congestion levels vary, and because the congestion level prior to the crash will be considered jointly with congestion caused by the crash. Several studies suggest that congestion may impact different crash types in different manners, though the types of crashes in focus and the findings are not necessarily consistent between studies. If different crash types related differently to congestion, this could be a source of bias for studies in which this has not been considered.

2.3 CONCLUSION

Seven studies were reviewed and summarized. Three studies find that a higher vehicle to capacity ratio is associated with fewer single-vehicle crashes, but the effect on multi-vehicle crashes is not consistent across studies. Studies investigating congestion based on speed or travel time generally find congestion to increase crash frequencies, but this is not found in all conditions in all studies. The effect of congestion on crash severity might depend on whether the traffic flow is stable or unstable, but this has only been investigated by one study. Generally, unstable traffic flow and speed variation, which is found in congested traffic, is found to be associated with increased crash risk. More research is needed to establish the relationship between congestion and road safety for different road types, road users, and countries.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature search strategy

The literature search was conducted in Science Direct and Taylor & Francis, and the main search terms were variations of *congestion*, *queue* and *v/c-ratio*, limited to studies published after 1999 in the English language. The search focused on hits in the titles, abstracts and key words of journal articles and reports. In addition to this structured search, results relevant for congestion were identified in studies coded primarily for the AADT risk factor. Titles and abstracts were screened during the search, and studies of potential relevance were screened full-text to assess relevance.

3.1.2 Principles

Limitations/exclusions for search in all databases:

- Title-ABSTR-KEY
- Journal articles and reports
- 2000-2016
- English language

3.1.3 Search terms and hits

Database: Science Direct **Date:** 15th of March 2016

search no.	search terms / operators / combined queries	hits
#1	TITLE-ABSTR-KEY(congestion or queue*) and TITLE-ABSTR-KEY(accident* or crash* or road safety).	130
#2	TITLE-ABSTR-KEY("congestion" or "congested" or queue* or "volume capacity ratio" OR "V/C ratio") and TITLE-ABSTR-KEY(accident* or crash* or "road safety" or injur* OR incident*)	655

Database: Taylor & Francis **Date:** 15th of March 2016

search no.	search terms / operators / combined queries	hits
#1	(congestion OR queuing OR V/C ratio) AND (traffic) AND (accident* OR crash* OR "road safety")	3917
#2	Article title: (accident* OR risk OR crash* OR safety) AND congestion	7
#3	Article title: (accident* OR risk OR crash* OR safety) AND (congestion OR queue*)	13

As noted, studies where titles and/or abstracts appeared relevant were obtained for full-text screening. Additionally, reference lists of most relevant studies were examined, resulting in a total of 26 studies to screen full text. To prioritize studies for coding, the following elimination criteria were applied:

- Studies were covered by meta-analysis (coded for the AADT risk factor)
- No crash data included in analysis
- Duplicate data

The remaining studies were assigned a lower priority if there was:

- Highly aggregated data (e.g. traffic zones)
- Results not compatible with coding (e.g. review, or descriptive results only)
- Very general or imprecise indicators of congestion only (e.g. peak hour/non-peak hour)

7 studies with the highest priority were coded for the repository.

3.2 CODED STUDIES

Daniel, J. R., & Maina, E. (2011). Relating Safety and Capacity on Urban Freeways. Procedia - Social and Behavioral Sciences, 16, 317–328. doi:10.1016/j.sbspro.2011.04.453

Golob, T. F., Recker, W., & Pavlis, Y. (2008). Probabilistic models of freeway safety performance using traffic flow data as predictors. Safety Science, 46(9), 1306–1333. doi:10.1016/j.ssci.2007.08.007

Ivan, J. N., Wang, C., & Bernardo, N. R. (2000). Explaining two-lane highway crash rates using land use and hourly exposure. Accident Analysis & Prevention, 32(6), 787–795. doi:10.1016/S0001-4575(99)00132-3

Lord, D., Manar, A., & Vizioli, A. (2005). Modeling crash-flow-density and crash-flow-V/C ratio relationships for rural and urban freeway segments. Accident; Analysis and Prevention, 37(1), 185–99. doi:10.1016/j.aap.2004.07.003

Shi, Q., Abdel-Aty, M., & Lee, J. (2016). A Bayesian ridge regression analysis of congestion's impact on urban expressway safety. Accident; Analysis and Prevention, 88, 124–37. doi:10.1016/j.aap.2015.12.001

Wang, C., Quddus, M., & Ison, S. (2013b). A spatio-temporal analysis of the impact of congestion on traffic safety on major roads in the UK. Transportmetrica, 9935(July 2015), 1–25. doi:10.1080/18128602.2010.538871

Zheng, Z. (2012). Empirical Analysis on Relationship between Traffic Conditions and Crash Occurrences. Procedia - Social and Behavioral Sciences, 43, 302–312. doi:10.1016/j.sbspro.2012.04.103

Studies screened full-text and rejected or given lower priority

Albalate, D., Fernández-villadangos, L., Albalate, D., & Andez-villadangos, L. F. (2010). Motorcycle Injury Severity in Barcelona : The Role of Vehicle Type and Congestion Motorcycle Injury Severity in Barcelona : The Role. Traffic Injury Prevention, (11), 632–631. Doi:10.1080/15389588.2010.506932

Christoforou, Z., Cohen, S., & Karlaftis, M. G. (2011). Identifying crash type propensity using real-time traffic data on freeways. Journal of Safety Research, 42(1), 43–50. doi:10.1016/j.jsr.2011.01.001

Golob, T. F., & Recker, W. W. (2003). Relationships Among Urban Freeway Accidents, Traffic Flow, Weather, and Lighting Conditions. Journal of Transportation Engineering, 129(August), 342–353. doi:10.1061/(ASCE)0733-947X(2003)129:4(342)

Golob, T. F., & Recker, W. W. (2004). A method for relating type of crash to traffic flow characteristics on urban freeways. Transportation Research Part A: Policy and Practice, 38(1), 53–80. doi:10.1016/j.tra.2003.08.002

Golob, T. F., Recker, W. W., & Alvarez, V. M. (2004). Freeway safety as a function of traffic flow. Accident; Analysis and Prevention, 36(6), 933–46. doi:10.1016/j.aap.2003.09.006

Hadayeghi, A., Shalaby, A. S., & Persaud, B. N. (2003). Macrolevel Accident Prediction Models for Evaluating Safety of Urban Transportation Systems. Transportation Research Record, 1840(03), 87–95.

Hossain, M., & Muromachi, Y. (2013). Understanding crash mechanism on urban expressways using high-resolution traffic data. Accident; Analysis and Prevention, 57, 17–29. doi:10.1016/j.aap.2013.03.024

Kononov, J., Bailey, B., & Allery, B. K. (2008). Relationships Between Safety and Both Congestion and Number of Lanes on Urban Freeways. Transportation Research Record: Journal of the Transportation Research Board, 2083(-1), 26–39. doi:10.3141/2083-04

Kwak, H.-C., & Kho, S. (2016). Predicting crash risk and identifying crash precursors on Korean expressways using loop detector data. Accident Analysis & Prevention, 88, 9–19. doi:10.1016/j.aap.2015.12.004

Martin, J.-L. (2002). Relationship between crash rate and hourly traffic flow on interurban motorways. Accident Analysis & Prevention, 34(5), 619–629. doi:10.1016/S0001-4575(01)00061-6

Noland, R. B., & Quddus, M. A. (2005). Congestion and safety: A spatial analysis of London. Transportation Research Part A: Policy and Practice, 39(7-9), 737–754. doi:10.1016/j.tra.2005.02.022

Sun, J., Li, T., Li, F., & Chen, F. (2015). Analysis of safety factors for urban expressways considering the effect of congestion in Shanghai, China. Accident; Analysis and Prevention. doi:10.1016/j.aap.2015.12.011

Tsai, J.-F., Chu, C.-P., & Hu, S.-R. (2015). Road pricing for congestion and accident externalities for mixed traffic of motorcycles and automobiles. Transportation Research Part A: Policy and Practice, 71, 153–166. doi:10.1016/j.tra.2014.10.020

Wang, C., Quddus, M. A., & Ison, S. G. (2009). Impact of traffic congestion on road accidents: a spatial analysis of the M25 motorway in England. Accident; Analysis and Prevention, 41(4), 798–808. doi:10.1016/j.aap.2009.04.002

Wang, C., Quddus, M. A., & Ison, S. G. (2013a). The effect of traffic and road characteristics on road safety: A review and future research direction. Safety Science, 57, 264–275. doi:10.1016/j.ssci.2013.02.012

Xu, C., Liu, P., Wang, W., & Li, Z. (2014). Identification of freeway crash-prone traffic conditions for traffic flow at different levels of service. Transportation Research Part A: Policy and Practice, 69, 58–70. doi:10.1016/j.tra.2014.08.011

Xu, C., Tarko, A. P., Wang, W., & Liu, P. (2013). Predicting crash likelihood and severity on freeways with real-time loop detector data. Accident; Analysis and Prevention, 57, 30–9. doi:10.1016/j.aap.2013.03.035

Xu, C., Wang, W., Liu, P., & Zhang, F. (2014). Development of a real-time crash risk prediction model incorporating the various crash mechanisms across different traffic states. Traffic Injury Prevention, 16(1), 28–35. doi:10.1080/15389588.2014.909036

Yeo, H., Jang, K., Skabardonis, A., & Kang, S. (2013). Impact of traffic states on freeway crash involvement rates. Accident; Analysis and Prevention, 50, 713–23. doi:10.1016/j.aap.2012.06.023

DESCRIPTIONS OF CODED STUDIES

Below, the sampling frames of the reviewed studies are presented in table 3, and an overview of methodologies and analyses is outlined in Table 4.

Table 3. Sampling frames and congestion indicators

Author(s), year, country	Area, time period	Congestion indicator
Lord et al., 2005, Canada	5 years (1994-1998), Montreal area. Urban (5 km) and rural (40 km) motorway sections. 1152 rural observations (time periods; sections; directions) and 144 urban observations (time periods; directions) were analysed. The urban dataset contained a total of 2817 crashes, the rural one 1865 crashes.	V/C-ratio estimated from procedure in HCM 2000. Traffic estimates from loop detector data averaged for similar hours.
Golob et al., 2008, USA	6 Months of crash- and traffic data from six major highways in California. Mainline crashes only.	Based on principal component analysis of disaggregated loop detector data (means, standard deviations and autocorrelations of raw data, 30 sec intervals); separate indicators for congestion in outer and inner lanes.
Ivan et al., 2000, USA	6 years of crash- and traffic data form rural 2-lane highway in Connecticut, N=4167 observations. 102 single-vehicle crashes and 220 multi-vehicle crashes.	V/C-ratio based on HCM 1994 for rural 2-lane highway segments.
Shi et al., 2016, USA	Urban motorway in central Florida, 21 miles, 2 years of data (2012-2014). N=396 observations, and 705 crashes. Mainline crashes only, weekend and night-time crashes are excluded.	Congestion index: ((free flow speed - actual speed)/free flow speed); SD of speed.
Wang et al., 2013, UK	Major roads including motorways. Traffic and crash data from 2003-2007. Total road length around 1400 km. N =1330. Junction crashes excluded.	Travel time delay: segment-based congestion measured as total delay (in seconds) per kilometre, i.e. the traffic delay incurred on all vehicles travelling along a road segment in a year.
Zheng, 2012, USA	A 9,6 -mile section of a freeway, 2 months of traffic- and crash data collected in peak periods. Total 145 crashes, N observations not reported.	Three traffic conditions: free flow (high speed, low occupancy), transition to/from congestion (fluctuating speed and occupancy) and congestion (lower speed; high occupancy).
Daniel & Maina, 2011, USA	Urban and rural freeways and arterials in New Jersey; 987 segments on 9 roadways, for which annual traffic data and 1 year of crash data was obtained. N=987 observations.	V/C-ratio, annual average per road segment.

Table 4. Methodological overview.

Author(s), year, country	Design, analysis	Outcome	Control variables
Lord et al., 2005, Canada	Observational, generalized negative binomial	Crash frequency, separate estimates all; severe + fatal; single-vehicle; multi-vehicle; urban; rural	Analysed units are different combinations of hour of day*weekday/Sat/Sun in addition to section.
Golob et al., 2008, USA	Observational, binomial logit for severity, multinomial logit for collision type	Severity; Collision type (i.e. side-swipe; rear-end etc.)	Other traffic variables from PCA of loop detector data (e.g. flow level, flow consistency across lanes)
Ivan et al., 2000, USA	Observational, non-linear poisson.	Crash rate per observation, separately for MV and SV	Time of day; % of section with no passing; shoulder width; intersections; number of driveways. Light conditions taken into account in defining observational units.
Shi et al., 2016, USA	Observational; Bayesian model with correlated random effects and random parameters; random parameter multilevel ridge regression model with	Crash frequency (total crashes and also PDO and KABC separately)	Section length; horizontal degree of curvature (not for different severities); number of lanes; speed limit; auxiliary lane (SD of speed in PDO/KABC)

	correlated random effects		
Wang et al., 2013, UK	Observational, time series. Bayesian spatial model (with spatial correlation).	Crash frequency per segment, annual level aggregation.	AADT; maximum gradient; number of lanes; speed limit; motorway; year; spatial correlation
Zheng, 2012, USA	Observational, logit.	Crash risk	None
Daniel & Maina, 2011, USA	Observational, negative binomial model	Crash frequency, all crashes.	Aadt; section length; % trucks: speed limit; number of lanes; lane width; shoulder width; ramp density for first analysis. aadt; v/c-ratio; posted speed for second analysis.

DETAILS OF STUDY RESULTS

Detailed overview of the results

Table 5 gives more detailed results of the studies focusing on v/c-ratio.

Table 5. Overview of study results. For v/c ratio

Author(s), year, country	Outcome	Crash type	Effect on outcome
Lord et al., 2005, Canada	Crash frequency	Single-vehicle	↘
		Multi-vehicle	↗
		All	↘
Ivan et al., 2000, USA	Crash rate	Single-vehicle	↘
		Multi-vehicle	-
Daniel & Maina, 2011, USA	Crash frequency	All	↘

Golob et al (2008) report that the effect of congestion on crash severity depends on which lane(s) the congestion occurs in: Right-lane congestion alone is found not to impact crash severity, while outer lanes congestion is associated with lower risk of injury crashes, and even more so when all lanes are congested. The authors suggest this might be related to lane-changing behaviour. They also find that congestion is related to rear-end and side-swipe crashes, but not to single vehicle hit-object crashes. It should be noted, however, that while data-driven approaches such as that applied in this study is sensitive to specific traffic conditions directly before a crash occurrence, the approach could also limit the generalizability of the study results to other datasets.

ADDITIONAL REFERENCES

Elvik, R. (2014). *Speed and road safety - new models*. TØI report 1296/2014. Oslo, Institute of Transport Economics.

Transportation Research Board (2001). *Highway Capacity Manual*, Transportation Research Board, Washington, DC.

Roshandel, S., Zheng, Z., & Washington, S. (2015). *Impact of real-time traffic characteristics on freeway crash occurrence: systematic review and meta-analysis.* Accident; analysis and prevention, 79, 198-211. doi:10.1016/j.aap.2015.03.013

Wang, C., Quddus, M, & Ison, S. (2009) *Impact of traffic congestion on road accidents: a spatial analysis of the M25 motorway in England*. Accident Analysis and Prevention, 41, 798-808.

Wang, C., Quddus, M, & Ison, S. (2013). *The effect of traffic and road characteristics on road safety: A review and future research direction*. Safety Science, 57, 264-275.

Synopsis 3: Occurrence of Secondary crashes

1 Summary

Hesjevoll, I. S., August 2016

COLOUR CODE: YELLOW

Explanation: The presence of a crash or an incident can contribute to the occurrence of additional (secondary) incidents or crashes. The prevalence of secondary crashes, and the factors contributing to their occurrence is unclear, as this varies between studies.

KEYWORDS

Secondary accident; secondary crash; secondary incident; incident; accident; crash; non-recurrent congestion; congestion; queue

1.1 ABSTRACT

The occurrence of an initial crash or incident (e.g. vehicle breakdown) may increase the risk of secondary crashes and incidents occurring, by causing (non-recurrent) congestion, traffic flow disruption and/or driver distraction. Studies find that 0.4 to 8.4 % of crashes on motorways are secondary, i.e. caused at least in part by a prior crash or incident. Most secondary crashes occur in the same direction and upstream of a prior crash, and a longer duration of the prior crash/incident is associated with greater risk of secondary crash occurrence. The methodology applied for classifying crashes as secondary varies greatly among studies, but is generally based on estimates of the queue caused by the prior crash/incident. The available literature has not investigated the extent of secondary crashes on roads other than motorways, nor the risk for different transportation modes.

1.2 BACKGROUND

1.2.1 How does incident occurrence affect road safety?

Two main mechanisms are generally proposed to explain how a prior incident or crash could contribute to the occurrence of a secondary incident or crash: First, risk may increase as the prior incident or crash causes congestion or disruptions in traffic flow. This could increase the complexity of driving, posing a risk for further crash occurrence. Secondly, a crash or an incident may cause driver distraction (rubbernecking), which could increase the risk of secondary occurrences.

1.2.2 How are crashes identified as secondary?

Information about whether an incident/a crash was induced (in part) by a prior occurrence is generally not available from accident databases. Thus, studies classify crashes as independent, primary or secondary by estimating a spatiotemporal "impact area" for each potential primary event, within which any subsequent crash/incident would be classified as secondary. Generally, the impact area is defined by the length and duration of the queue/traffic flow disruption caused by the prior incident, and in many cases it also includes the potential for rubbernecking crashes. There are many methods for estimating impact areas. Earlier studies relied on static definitions of impact areas (e.g. 1 hour and 5 km from each crash), which results in misclassifications (Sarker et al., 2015). All coded studies rely on dynamic definitions of impact areas, defining a different one for each potential primary crash. These impact areas are generally based on crash/incident characteristics (e.g. duration, lanes blocked) and/or traffic conditions (based on either average or real-time data).

1.2.3 Which safety outcomes are affected by crashes/incidents?

The reviewed studies generally focus on two things. In several studies, the main focus is estimating the prevalence of secondary incidents. In addition to this, some studies investigate which characteristics of prior crashes that affect the risk of secondary occurrences.

1.2.4 How common are secondary crashes?

In the coded studies, the prevalence of secondary crashes varies from 0.4 to 8.4% of all crashes. The vast majority of primary crashes/incidents are associated with no more than one secondary crash/incident. Most secondary crashes occur in the same direction and upstream of a prior crash/incident with an average distance of 2-3 km (Chung, 2013; Zheng et al, 2015), but the average time gaps between primary and secondary crash/incident varies between studies (17 to 66 min). The prevalence on road types other than motorways is not known.

1.2.5 How is the effect of crashes/incidents on road safety studied?

Some of the coded studies are mainly concerned with classifying crashes as primary, secondary or independent. Studies that investigate the risk of secondary crash occurrence typically use a case-control design, in which the characteristics of primary crashes/incidents are compared to those of independent crashes/incidents. Crash/incident characteristics investigated include, among others: crash severity, lane blockage, road environment characteristics, involved parties, duration and time of day. Characteristics that more frequently occur among primary than independent incidents are said to increase the risk of secondary crash occurrence. The studies differ with respect to the type of occurrences they investigate: some investigate all or specific types of potential primary incidents (e.g. lane blockage incidents), while others focus on crashes. All studies are based on motorways.

1.3 OVERVIEW OF RESULTS

All coded studies identify pairs of primary and secondary crashes/incidents. From the four studies comparing characteristics of primary and independent crashes/incidents, results show that:

- A longer duration of the prior crashes/incidents is associated with an increased risk of secondary crash occurrence (4/4 studies).
- Crashes/incidents occurring in daytime and peak periods seem to be associated with a greater risk of secondary crash occurrence than occurrences at other hours (2/2 studies).
- Crashes are associated with a greater risk of secondary occurrences than other incidents (2/2 studies)

1.3.1 Transferability

All coded studies are based on data from motorways in the United States. With the exception of truck involvement in the prior crash/incidents, little is known about different road users.

1.3.2 Notes on analysis methods

This risk factor has not been studied extensively, and due to the limited number of studies being rather dissimilar with respect to sampling frames (incidents or crashes), classification methods and crash characteristics investigated, the transferability of secondary occurrence prevalence and crash characteristics related to the risk of secondary occurrences is limited. This is especially the case for non-motorways, different road users and countries other than the U.S.

The dynamic methods applied to identify crashes as secondary are likely to correctly classify the majority of crashes as primary, secondary or independent, therefore studies should be considered as good quality. However, most studies have not attempted or been able to verify whether the crashes classified as secondary were for certain induced (at least in part) by the prior crash. This leaves some uncertainty in the results, particularly for possible secondary crashes/incidents caused by distraction.

2 Scientific overview

2.1 LITERATURE REVIEW

2.1.1 Defining secondary crashes and the mechanisms by which they occur

The methods applied to identify secondary occurrences in the coded studies assume two different main mechanisms by which an incident could contribute to the occurrence of a secondary crash: congestion / traffic flow and driver distraction.

All methodologies allow for and put the main emphasis on the occurrence of secondary crashes/incidents induced by **congestion or traffic flow disruption** resulting from the prior incident. Most approaches define a congested spatiotemporal region or impact area of disrupted traffic flow caused by the primary crash or incident, and classify crashes occurring within this impact area as secondary. Some, but not all studies also estimate a congested impact area in the opposite direction.

Earlier classifications of secondary crashes employed static spatiotemporal thresholds for impact areas, e.g. 15 min and 1 mile upstream from each crash. This is problematic because the impact area of a crash depends on the traffic conditions at the time and place where it occurred: Studies have shown this approach to lead to both false positive and false negative secondary crash classification (see e.g. Sarker, Naimi, Mishra, Golias, & Freeze, 2015).

More recent approaches, including all coded studies, apply dynamic definitions of impact areas, so that a different spatiotemporal impact area is estimated for each crash/incidents. The methods applied to identify congestion-induced secondary occurrences vary with respect to both principles and complexity. Several studies apply queueing models to estimate the length of the queue caused by a crash. Impact areas are modelled as a multivariate function of crash/incident characteristics such as incident duration and the number of lanes blocked, and traffic conditions (based either on average traffic data for the area and time period of each crash or real-time traffic data). Both deterministic or shock-wave based queueing models have been applied, often based on the methodologies of the Highway Capacity Manual. Additionally, some studies have developed new methods to define impact areas, e.g. plotting real-time congestion and isolating the non-recurrent congestion from spatiotemporal regions with recurrent congestion. In contrast, studies based on traditional queueing models include recurrent congestion in defining the impact area.

All approaches have shortcomings. While relying on average estimates of traffic conditions may result in imprecise estimates, approaches relying on real-time data are prone to missing data. Queueing models also require detailed data on duration, clearance time and lane blockage, which is often not available, and some approaches assume that the impact area of the primary crash ends at clearance time, which is not necessarily the case.

The second mechanism explicitly considered by some studies is **driver distraction** occurring as drivers observe the crash/incident (i.e. rubbernecking), which could also cause congestion. Distraction-related secondary occurrences are taken into account in two ways: First, such occurrences are identified if the areas in which they occur are found/estimated to be congested. Secondly, static thresholds for the opposite direction such as "within incident duration and segment" or "within 1 mile and 1 hour" are sometimes used to identify distraction-related secondary incidents. Thus, the applied approaches for crash/incident classification are more methodologically sound for congestion-induced secondary crashes than for those induced by distraction. Still, studies not taking the potential rubbernecking-crashes into account will probably underestimate the prevalence of secondary crashes/incidents.

2.2 DESCRIPTION OF STUDIES

Seven studies were identified, of which three were mainly concerned with the classification of crashes/incidents as primary, secondary or independent, and the remaining four also addressed the risk of secondary crash/incident occurrence.

2.2.1 Sampling frames, definitions, and prevalence.

Table 1 displays how crashes are identified as secondary in the coded studies, and the prevalence of secondary crashes/incidents identified. The directions in which the impact area is defined are also outlined: Some studies define impact areas only in the same direction (SD) upstream of the incident, others allow the impact area to also include the opposite travelling direction (OD), and/or downstream in the same direction.

Table 1. Sampling frames and secondary crash/incident identification.

Author(s), year, country	**Sampling frame for classification**	**Method for crash/incident classification, traffic data, and direction(s) of impact area**	**Prevalence of primary and/or secondary crashes**
Junhua et al, 2016, USA	All freeway interstate crashes in California, 3 years (2010-2012), n = 49573 crashes.	Shock-wave boundary filtering, estimating scope of real-time shock waves (at occurrence, at arrival of rescue personnel/police, and at queue dissipation) created by each potential primary incident. Real-time traffic sensor data. SD: U	204 accident pairs, and 209 secondary crashes, were identified, which corresponds to 0.4 % of total crashes considered.
Yang et al, 2014, USA	A 27-mile freeway section in New Jersey Turnpike with 1 year of crash data (2011). N = 1188 crashes.	"Speed contour plot", defined as non-recurrent congestion caused by each potential primary crash in either direction. Recurrent congestion is controlled for based on historical data. Real-time traffic sensor data (speed). Additionally, OD:U is classified as secondary if they occur within 1h and 1 mile from the primary. SD: U, D; OD: U	71 primary crashes induced 100 secondary crashes. 5.9 % of crashes caused a secondary crash. 8.4 % of crashes were secondary.
Zhan et al, 2009, USA	Three major freeway corridors, Florida. From 2 years (Jan 2005- Jan 2007) of lane blockage incidents (n = 4435), secondary crashes are identified. Total crashes before identification = 7930	Deterministic queueing model: Cumulative arrival and departure curve technique based on lane blockage information and average volume estimates for the time and place of the (prior) incident. Impact area is the maximum possible queue length and within the queue dissipation time of the prior crash. SD: U	5 % of incidents were primary, and 2.8 % of crashes were secondary. For different roads, the percentage of crashes that are secondary varies from 0.1 to 4.3 %, while the percentage of lane blockage incidents that are primary varies from 2.2 to 5.9 %.
Zhang & Khattak, 2010, USA	Hampton roads area, highway incidents from 1 year (2005), n = 34209 incidents.	Deterministic queueing model: Cumulative arrival and departure curve technique based on lane blockage information and average volume estimates for the time and place of the (prior) incident. SD: U; OD: within duration, and segment, and visible according to criteria such as no visual median barrier present.	3 % of incidents are associated with 1 or more secondary incident, and less than 1 % (136 incidents) were associated with 2 or more secondary incidents. Prevalence varies between road segments.
Zheng et al, 2015, USA	A 1500-mile freeway section, 5 years (2007-2011) of crash- and traffic data from Wisconsin. Annual crashes n = 12500-15500.	Two steps: 1) Automatically, based on queueing model with impact area defined by the queuing and discharging shockwaves based on average traffic data. 2) Manually verified based on police report narratives. SD: U, D; OD: U, D	Verified distinct secondary crashes make up 0.3-0.6 % of all crashes each year. In step 1, 7-11 % of crashes are classified as secondary for each year (including potential cases with missing traffic data).

Chung, 2013, USA	Six freeway sections in Orange County, California. crashes from 2001 (total n=6200, but n=1890 used in analysis).	Spatiotemporal speed matrix; maximum extent of crash influence (crash and clearing shockwaves), and leaving out recurrent congested areas to isolate the non-recurrent speed reduction caused by the crash. Also includes any crash that occurred within section of prior crash and average duration period in study area. SD: U, D; OD: U, D	Secondary crashes in the same and opposite directions are identified to be 7.4% and 3.8% of total primary crashes, respectively. 0.3% of total primary crashes are connected with secondary crashes in both directions
Sarker et al, 2015, USA	282 miles of freeway, 1337 miles of arterials in Shelby County, Tennessee. crashes from three years (2010-2012). Total n = 91325*	Freeway: Queue lengths estimated by shock waves (back and front of queue) both directions, verified by video. Static for comparison. Based on real-time sensor data. Arterials: various static thresholds.SD: U, OD: U, D	235 secondary crashes identified on freeways based on dynamic method. Prevalence of on arterials varies greatly by thresholds for impact areas.

Note: *not clear how many of these are for freeways, and the estimates based on static thresholds have not been coded and will not be elaborated further. SD: same direction, OD: opposite direction, U: upstream, D: downstream.

The prevalence of secondary crashes/incidents varies between studies. Differences in prevalence could originate from any of the aspect by which the studies differ, such as type of traffic data (average or disaggregated), type of occurrences studied (crashes/incidents), methods and directions for identifying secondary crashes/incidents, or actual differences in prevalence between the road sections studied.

All studies find secondary crashes/incidents occurring in the same direction upstream to be more prevalent than secondary crashes in the opposite direction and in the same direction upstream. Both Sarker et al. (2015) and Zheng et al. (2015) find that 60 % of secondary crashes occur in the same direction as and upstream of the primary crash. It is also found that the majority of primary crashes are associated with no more than one secondary crash. Chung (2013) finds that among secondary crashes in the same direction, 82 % are "primary secondary", (i.e. a first secondary crash, in contrast to a second or third secondary crash when one primary crash is associated with multiple secondary occurrences), while the corresponding number in the opposite direction is 92 %.

2.2.2 How is the effect of crashes/incidents on road safety studied?

Among the seven coded studies, four investigate incident characteristics related to the probability of secondary crash/incident occurrence, while the remaining three are mainly concerned with defining and identifying crashes/incidents as independent, primary or secondary. All four studies investigating crash/incident characteristics related to the probability of secondary crash/incident occurrence are case-control studies in which incidents associated with the occurrence of one or more secondary incident(s) are compared with independent incidents not related to any secondary occurrence. Three of the four studies analyse the data by means of a binary logistic regression model, one of which uses a rare event logistic regression (Zhan et al, 2009). The fourth study applies a generalized logit model with a three-level outcome variable (the occurrence of 0, 1 or 2 secondary crashes).

2.2.3 Limitations

While the approaches applied to classify crashes as primary, secondary or independent appear likely to result in many correct classifications, they remain estimates, leaving some uncertainty in the results. This is especially the case for possible secondary crashes/incidents caused by distraction.

2.2.4 How well has the effect of crashes/incidents been studied?

No studies were found that used dynamic definitions of impact areas on roads other than motorways. This is unsurprising, and probably in part due to methodological difficulties: The procedures used to identify secondary crashes require rich and detailed data on crash locations and traffic conditions, and many methods rely on the traffic flow being continuous, which might not be the case for arterial roads (e.g. due to intersections). All coded studies are based on data from the United States, and little attention has been given to different road users.

2.2.5 Transferability

In the sense that all studies identify a number of crashes as secondary, the evidence is clear on the potential of crashes/incidents to induce subsequent crash occurrence. Concerning the prevalence of secondary crashes, the limited number of studies and the differences between them with regard to both methodologies and results (prevalence), indicates limited potential for transferability, especially for different road types. Similarly, for crash characteristics related to the risk of secondary occurrences, few and heterogeneous results indicate limited generalizability.

2.3 DESCRIPTION OF ANALYSIS CARRIED OUT

2.3.1 Vote-count analysis

Among the four case-control studies, only two used the same analysis, and one of these did not report indicators of the uncertainty of the results (SE or CI). Therefore, it was not possible to conduct a meta-analysis. Instead, the results have been summarized as a vote-count analysis, where each estimate (1 per study) gets one vote on the importance of a crash characteristic. Results are presented in Table 2 for crash/incident characteristics that have been investigated in a similar manner by at least two studies.

Consequently, the vote can take three different values:

- An increase in risk of secondary crash/incident (↗)
- A decrease in risk of secondary crash/incident (↘)
- No significant difference in risk of secondary crash/incident (-)

However, none of the crash characteristics summarized in the vote-count analysis were reported to decrease the risk of secondary occurrences.

Table 2. Summary of study results: crash/incident characteristics and their relation to secondary occurrences.

	Tested in number of studies	Result (number of studies)		Result (% of studies)	
		↗	-	↗	-
Duration	4	4		100%	
More than one lane blocked	2	1	1	50 %	50 %
Incident is accident	2	2		100%	
Crash severity	3		3		100%
Parties involved	3	1	2	33%	66%
Truck involved	3		3		100%
Daytime	2	2		100%	
Peak	2	2		100%	
Wet pavement	2		2		10%
Illumination; visibility	2		2		100%

All four studies find the duration of a prior incident or crash to be associated with increased secondary crash occurrence. Similarly, crashes and incidents are associated with increased risk of secondary crash occurrence if they occur in daytime and in peak hours, and crashes are associated with increased secondary crash/incident occurrence compared to incidents that are not crashes.

Due to the low number of studies as well as differences in methodologies applied to classify incidents as primary, secondary and independent, it is not possible to say with certainty to what extent differences between studies reflect systematic differences in the type of occurrences investigated (e.g. crashes versus lane blockage incidents, or impact areas including upstream same direction only vs both directions upstream and downstream).

In addition to the crash characteristics summarized above, which were investigated by at least two of the four studies, each study included some characteristics that were not investigated by any of the remaining studies. These results are summarized in the supporting document.

2.4 CONCLUSION

Seven studies investigating the prevalence of secondary crashes/incidents, among which four investigated crash/incident characteristics related to the risk of secondary occurrences have been coded, analysed and summarized. While all studies on crash characteristics related to secondary occurrences use case-control designs, differences in sampling frames, analyses and details reported rendered a meta-analysis impossible.

The vote-count analysis carried out showed that incident duration is associated with an increased risk of secondary occurrences in all studies. While investigated by fewer studies, it seems that crashes are associated with higher risk of secondary occurrences than incidents, and that incidents occurring in daytime generally but also in peak hours have higher odds of inducing secondary occurrences than incidents occurring at other times of the day. Crash severity, involvement of trucks, a wet road surface, illumination and visibility are not related to the risk of secondary occurrences. The effects of other crash characteristics are less clear.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature search strategy and principles

The literature search was conducted in Science Direct, Google Scholar, TRID, Springer Link and Taylor & Francis, with main search terms secondary accident (/incident/crash), limited to studies published after 1999 in the English language:

3.1.2 Research terms and hits

Database: Google Scholar **Date:** 10th of March 2016

- Published: 2000 to current

search no.	search terms / operators / combined queries	hits
#1	secondary accident*" OR "secondary crash *" [title only]	11
#2	"secondary accident *" OR "secondary crash *"	628
#3	("secondary accident*" OR "secondary crash* OR "secondary incident*) AND (traffic OR road* OR risk OR *ways)	274

Database: Science direct **Date:** 10th of March 2016

- Published: 2000 to current
- Only title, abstracts and keywords were searched

search no.	search terms / operators / combined queries	hits
#1	pub-date > 1999 and TITLE-ABSTR-KEY("secondary crash*") or TITLE-ABSTR-KEY("secondary accident*").	13
#2	TITLE-ABSTR-KEY("secondary accident*") OR TITLE-ABSTR-KEY ("secondary crash*") OR TITLE-ABSTR-KEY("secondary incident*")	23

Database: Taylor & Francis **Date:** 11th of March 2016

search no.	search terms / operators / combined queries	hits
#1	"secondary accident*" OR "secondary crash*" OR "secondary incident*"	34

Database: TRID **Date:** 11th of March 2016

search no.	search terms / operators / combined queries	hits
#1	"secondary accident*" OR "secondary crash*" OR "secondary incident*"	29

Database: Springer Link **Date:** 11th of March 2016

search no.	search terms / operators / combined queries	hits
#1	"secondary accident*" OR "secondary crash*" OR "secondary incident*" AND (traffic OR road* OR risk OR *ways) [articles]	68

3.1.3 Results of literature search and screening

After screening titles and abstracts in the searches, 24 studies were retrieved and screened full-text.
The elimination criteria for prioritizing coding among the studies screened full-text were as follows:

- Static spatiotemporal definition for identifying secondary crashes applied
- Duplicate data, e.g. report on which an article is based, in which case the article was given priority
- Not based on actual accident/incident data
- Results were not compatible with coding (e.g. due to unusual analysis)
- Lack of detail in reporting making the study design and/or analysis unclear (e.g. outcome variable not clearly defined)
- Analysis compares secondary crashes with primary *and* independent crashes on variables common to the primary and secondary crashes

3.1.4 Prioritizing Coding

Among the remaining studies, prioritization for coding was done by the following criteria:

- Provides information on factors related to the occurence or risk of secondary crashes/incidents
- Verification of accident classification
- Larger sample
- More sophisticated classification procedures

Finally, studies defining impact areas by use of average flow data for the section (e.g. monthly estimates) were given a lower priority than studies using more disaggregate data, as coded studies show temporal variations to be important in identifying secondary crashes correctly. In the end, seven studies with the highest priority according to the above listed criteria were selected for coding.

3.2 LISTS OF CODED AND CONSIDERED STUDIES

Coded studies

Chung, Y. (2013). *Identifying Primary and Secondary Crash from Spatio-temporal Crash Impact Analysis*. Transportation Research Board 92nd Annual Meeting, 1148(2386), 1–15. doi:10.3141/2386-08

Junhua, W., Boya, L., Lanfang, Z., & Ragland, D. R. (2016*). Modelling secondary accidents identified by traffic shock waves*. Accident; Analysis and Prevention, 87, 141–7. doi:10.1016/j.aap.2015.11.031

Sarker, A. A., Naimi, A., Mishra, S., Golias, M. M., & Freeze, P. B. (2015). Development of a Secondary Crash Identification Algorithm and occurrence pattern determination in large scale multi-facility transportation network. Transportation Research Part C: Emerging Technologies, 60, 142–160. doi:10.1016/j.trc.2015.08.011

Yang, H., Ozbay, K., & Xie, K. (2014). *Assessing the risk of secondary crashes on highways*. Journal of Safety Research, 49, 143–9. doi:10.1016/j.jsr.2014.03.007

Zhan, C., Gan, A., & Hadi, M. (2009). *Identifying Secondary Crashes and Their Contributing Factors.* Transportation Research Record: Journal of the Transportation Research Board, 2102(-1), 68–75. doi:10.3141/2102-09

Zhang, H., & Khattak, A. (2010). *What Is the Role of Multiple Secondary Incidents in Traffic Operations?* Journal of Transportation Engineering, 136(November), 986–997. doi:10.1061/(ASCE)TE.1943-5436.0000164

Zheng, D., Chitturi, M. V., Bill, A. R., & Noyce, D. A. (2015). *Analyses of Multiyear Statewide Secondary Crash Data and Automatic Crash Report Reviewing*. Transportation Research Record: Journal of the Transportation Research Board, 2514(2514), 117–128. doi:10.3141/2514-13

Studies screened and rejected based on abovementioned criteria

Chimba, D., & Kutela, B. (2014). Scanning secondary derived crashes from disabled and abandoned vehicle incidents on uninterrupted flow highways. Journal of Safety Research, 50, 109–16. doi:10.1016/j.jsr.2014.05.004

Karlaftis, M. G., Latoski, S. P., Richards, N. J., & Sinha, K. C. (1999). ITS Impacts on Safety and Traffic Management: An Investigation of Secondary Crash Causes. ITS Journal - Intelligent Transportation Systems Journal, 5(1), 39–52. doi:10.1080/10248079908903756

Khattak, A. J., Wang, X., & Zhang, H. (2010). Spatial Analysis and Modeling of Traffic Incidents for Proactive Incident Management and Strategic Planning.

Transportation Research Record: Journal of the Transportation Research Board, (2178), 128–137. doi:10.3141/2178-14

Khattak, A., Wang, X., & Zhang, H. (2009). Are Incident Durations and Secondary Incidents Interdependent? Transportation Research Record: Journal of the Transportation Research Board, 2099(-1), 39–49. doi:10.3141/2099-05

Li, F., Li, W., & Xie, F. (2011). Study on Finite Element Model of Traffic Flow based on Weighted Residual Method. Procedia Engineering, 24, 495–499. doi:10.1016/j.proeng.2011.11.2683

Li, R., Pereira, F. C., & Ben-Akiva, M. E. (2015). Competing risks mixture model for traffic incident duration prediction. Accident; Analysis and Prevention, 75, 192–201. doi:10.1016/j.aap.2014.11.023

Moore, J., Giuliano, G., & Cho, S. (2004). Secondary accident rates on Los Angeles freeways. Journal of Transportation Engineering, 130(3), 280–285.

Park, H., & Haghani, A. (2015). Real-time prediction of secondary incident occurrences using vehicle probe data. Transportation Research Part C: Emerging Technologies. doi:10.1016/j.trc.2015.03.018

Vlahogianni, E. I., Karlaftis, M. G., Golias, J. C., & Halkias, B. M. (2010). Freeway Operations, Spatiotemporal-Incident Characteristics, and Secondary-Crash Occurrence. Transportation Research Record: Journal of the Transportation Research Board, (2178), 1–9. doi:10.3141/2178-01

Vlahogianni, E. I., Karlaftis, M. G., & Orfanou, F. P. (2012). Modeling the Effects of Weather and Traffic on the Risk of Secondary Incidents. Journal of Intelligent Transportation Systems, 16(3), 109–117. doi:10.1080/15472450.2012.688384

Yang, H., Bartin, B., & Ozbay, K. (2013). Identifying Secondary Crashes on Freeways Using Sensor Data. Transportation Research Board 92nd Annual Meeting, 1–16. doi:10.3141/2396-10

Yang, H., Bartin, B., & Ozbay, K. (2013). Use of Sensor Data to Identify Secondary Crashes on Freeways. Transportation Research Record, (2396), 82–92. doi:Doi 10.3141/2396-10

Yang, H., Ozbay, K., Morgul, E. F., Bartin, B., & Xie, K. (2014). Development of an Online Scalable Approach for Identifying Secondary Crashes. Transportation Research Record Journal of the Transportation Research Board, (26), 15–33. doi:10.3141/2470-03

Yu, Q. (2013). Causes and Prevention Measures of Secondary Rear-End Accidents in the Rescue of Highway Traffic Accidents. Procedia Engineering, 52, 571–577. doi:10.1016/j.proeng.2013.02.187

Zhang, H., & Khattak, A. (2011a). Spatiotemporal Patterns of Primary and Secondary Incidents on Urban Freeways. Transportation Research Record: Journal of the Transportation Research Board, 2229(-1), 19–27. doi:10.3141/2229-03

Zhang, H., & Khattak, A. J. (2011b). Analysis of Large-Scale Incidents on Urban Freeways. Transportation Research Record: Journal of the Transportation Research Board, 2178(2178), 30–39. doi:10.3141/2178-04

Zheng, D., Chitturi, M. V., Bill, A. R., & Noyce, D. A. (2014). Identification of Secondary Crashes on a Large-Scale Highway System. Transportation Research Record: Journal of the Transportation Research Board, (2432), 0361–1981. doi:10.3141/2432-10

Zhou, H., & Tian, Z. (2012). Modeling Analysis of Incident and Roadway Clearance Time. Procedia - Social and Behavioral Sciences, 43, 349–355. doi:10.1016/j.sbspro.2012.04.108

3.3 DETAILED OVERVIEW OF STUDY RESULTS

Four of the coded studies used a case-control design, comparing primary crashes with independent crashes, to investigate crash characteristics associated with increased risk of secondary crash occurrence. However, as only two of these studies used the same analysis method, of which one did not report any indication of the uncertainty of the results (standard error or confidence intervals), it was not possible to conduct a meta-analysis. Instead, the results have been summarized as a vote-count analysis, where each estimate (1 per study) gets one vote on the importance of a crash characteristic. Results are presented in table 5 for crash/incident characteristics that have been investigated in a similar manner by at least two studies.

Arrows reflect change in risk, with an upwards pointing arrow indicating increased risk of a secondary crash/incident occurring and vice versa. Straight lines indicate no significant effect (for which estimates are often not presented in the papers), while variables not investigated are left blank.

Table 3. Study results: Incident/crash characteristics related to secondary occurrences

Study	Sampling frame		Effect on risk of secondary crash/incident occurrence									
	Type of observations (primary/ secondary)	N cases, controls*	Duration	Incident is accident	Crash severity	n involved	truck involved	>1 lane blocked	daytime	peak	Wet pavement	illumination; visibility
Junhua et al, 2016	Accidents/ crashes	204, 979	↗		-	-					-	
Yang et al, 2014	Crashes/ crashes	71, 710	↗		-		-	↗	↗	↗		-
Zhan et al, 2009	lane blockage incidents/ crashes	221, 4214	↗	↗	-	-	-	-	↗	↗	-	
Zhang & Khattak, 2010	Incidents/ incidents	**3429****	↗	↗		↗	-					-
Result (% of studies)												
	↗		100	100	0	33	0	50	100	100	0	0
	-		0	0	100	66	100	50	0	0	100	100
	↘		0	0	0	0	0	0	0	0	0	0

Note: * For all studies, cases are primary incidents/accidents, and all controls are independent incidents/accidents ** Analysis is based on 3429 observations, but the exact numbers of primary and independent incidents are not stated. From a total of 36427 incidents, 35312 were not related to any secondary incident(s).

Several incident characteristics were addressed by only one study. These characteristics can be summarized as follows:

Zhang & Khattak (2010) found a larger number of lanes to be associated with increased secondary incident occurrence. On the other hand, incidents occurring in a curve are associated with lower odds of secondary incident occurrence. They also report lane blockage incidents to be associated with greater occurrence of secondary incidents than incidents that do not block any lanes. Yang et al. (2014) found that rear-end crashes are associated with a higher risk of secondary occurrences than other crashes. They also found that crashes occurring in the winter are associated with a lower risk of secondary occurrences.

Junhua et al. (2016) found the speed of the 2nd and 3rd shockwave (created upon arrival of rescue personnel or police and queue dissipation, respectively) increases the odds of secondary crash occurrence, while the speed of the first shockwave (from queue formation resulting from the prior crash) is related to lower odds of secondary crash occurrence. They also found that incidents caused in part by "unsafe speed" were related to increased occurrence of secondary crashes, while other violation categories were not significant.

Regarding traffic volume, Junhua et al. (2016) found that traffic volume measured at 5-minute intervals was not significant for secondary crash occurrence, while Zhang and Khattak (2010) found a higher AADT to be related to increased risk of secondary incidents.

An overview of the variables investigated in each study is outlined in Table 4.

1.1.1 Time and distance gaps

Regarding time and distance gaps, Zhang & Khattak (2010) find that within 20 minutes, more than 60 % of first secondary incidents would occur, and 40 % occurred within 10 minutes. The time gaps for second secondary incidents were more spread. Zheng and colleauges (2015) find that 99 % of secondary crashes occur within an hour, with an average time of 17 min. They also find the average distance in the same direction to be 0.29 mi, and 0.4 and 0,15 miles in the opposite direction upstream and downstream, respectively. However, Chung (2013), finds the average time- and distance gaps to be 1.34 miles and 66 minutes in the same direction, and 1.8 miles and 81 minutes in the opposite direction.

Table 4. Crash/incident characteristics investigated by case control studies.

Author(s), year, country	Sample (prior to classification)	Design, analysis	Variables investigated
Junhua et al, 2016, USA	All freeway interstate crashes in California, 3 years (2010-2012), n = 49573 crashes.	Case-control: Secondary crash occurrence vs independent crashes. Logistic regression.	• unsafe speed • weather • duration • speed of shock waves 1, 2 and 3 • crash severity* • violation category* • tow away* • parties involved* • road surface (wet/dry/snow/ice)* • lighting* • traffic volume*

Yang et al, 2014, USA	A 27-mile freeway section in New Jersey Turnpike with 1 year of crash data (2011). N = 1188 crashes.	Case-control: Secondary crash occurrence vs independent crashes. Rare event logistic regression.	• Time of day • peak hour/not • Crash type • Duration • lane closure • season • weekend* • work zone* • truck involved* • crash severity*
Zhan et al, 2009, USA	Three major freeway corridors, Florida. From 2 years (Jan 2005-Jan 2007) of lane blockage incidents (n = 4435), secondary crashes are identified.	Case-control. Secondary crash occurrence vs independent incidents. Logistic regression.	• ln(duration) • which road • time of day • incident type • crash severity* • parties involved* • vehicle type involved* • weather* • pavement condition* • visibility* • illumination* • v/c-ratio*
Zhang & Khattak, 2010, USA	Hampton roads area, highway incidents from 1 year (2005), n = 34.209 incidents.	Case-control: Secondary incidence occurrence – 0, 1 or 2+ secondary crashes. Generalized logit model.	• Incident type • truck involvement • n vehicles involved • outstate vehicle • segment length • n lanes • curve/not • AADT

Note: *Variables excluded from model results due to lack of statistical significance

Synopsis 4: Risks associated with varying traffic composition

1. Summary

Hesjevoll, I.S., August 2016

COLOUR CODE: RED

Explanation: As the share of cyclists and/or pedestrians in the traffic flow increases, the increase in the number of crashes is found to be less than would be expected for the proportional increase in traffic volume, indicating a lower risk for each road user at higher volumes. The effect of the share of HGVs on road safety is unclear.

KEYWORDS

Cyclist; Pedestrian; Traffic composition; Safety-in-numbers; Meta-analysis; HGVs; Traffic flow

1.1 ABSTRACT

Traffic composition refers to the share of different groups of road users in traffic (e.g. cars, pedestrians, cyclists, Heavy Goods Vehicle (HGV)s, Powered Two Wheelers). An increase in the volume of cyclists and pedestrians is associated with a net increase in crashes (between cyclists/ pedestrians and motor vehicles), but this increase is less than would be expected for the proportional increase in volume, corresponding to lower risk for each road user: A meta-analysis estimated that a doubling of the volumes of pedestrians or cyclists would correspond to a 41 % increase in crashes (across road types and areas). This is in accordance with a Safety-in-Numbers effect (more cyclists/ pedestrian corresponds to a lower crash risk for each cyclist/pedestrian), but it remains unclear if the lower risk is *caused* by the higher numbers of pedestrians/cyclists. The effect of the share of heavy goods vehicles on road safety is unclear (few studies with mixed results), and no studies were found on the share of PTWs or public transport.

1.2 BACKGROUND

1.1.1 What is traffic composition?

Traffic composition refers to the share of different groups of road users (e.g. cars, pedestrians, cyclists, HGVs, PTWs). Thus, a stream of traffic consisting of 10 % heavy vehicles, 80 % light vehicles and 10 % pedestrians or cyclists has a different composition from a traffic stream consisting of 5 % heavy vehicles, 75 % light vehicles and 20 % pedestrians or cyclists. Traffic composition differs between rural and urban roads and also between types of road. As an example, pedestrians and cyclists are not allowed to use motorways, but can make up more than 50 % of traffic in city centres.

1.1.2 How does traffic composition affect road safety?

The relationship between the share of pedestrians or cyclists and crash risk has been described as a "Safety-in-numbers" effect, i.e. that an increase in the volumes of cyclists/pedestrians is associated with a lower risk for each cyclist/pedestrian. It is not clear what mechanism is responsible for this association, but several have been proposed (here exemplified by cyclists): It might be that a higher number of cyclists causes the reduced risk, by make drivers more aware of cyclists or because increases in interactions between cyclists and motor vehicles improves the quality of these interactions or lowers the speed. Alternatively, the characteristics of the cyclist population could change as more cyclists enter the traffic (individuals who join the cyclist population at a later point in time could be more cautious than other cyclists, reducing the average risk for cyclists). Another possibility is that the mechanism goes in the opposite direction: more people walk and cycle where it is safe to do so. It may also be that the observed association is a result of some other (spurious) variable affecting both road user shares and crash frequency, for instance that the quality of the infrastructure available for cyclist affects both the road user share and crash risk.

Regarding HGV-share, both the effect on road safety and the mechanism by which this occurs is unclear, due to a small amount of studies reporting mixed results.

1.1.3 What road safety outcomes are affected by traffic composition?

The studies reviewed for the effect of traffic composition on road safety are all concerned with crash frequency; none focused on crash severity.

1.1.4 How is the effect of traffic composition on road safety studied?

Two main groups of studies are reviewed. The first group of studies address the volumes of cyclists/pedestrians and motor vehicles, and the Safety-in-numbers effect. Among these studies is one meta-analysis, covering studies from various settings (urban, rural), countries (mostly Northern Europe and North America) and levels of analysis (from cities to crossings).

The second group of studies in concerned with the share of heavy goods vehicles (in relation to cars/other motorized vehicles). The three studies are from Spain, Sweden and the United States, and they investigate different types of roads.

All studies are cross-sectional, using multivariate crash prediction models to explain variations in crash numbers.

1.3 OVERVIEW OF RESULTS

1.3.1 Main results

One meta-analysis based on 15 original studies, as well as two additional original studies, confirm a safety-in-numbers effect for both pedestrians and cyclists: as the volumes of pedestrians and cyclists increases, crash risk (for crashes involving pedestrians/cyclists and motor vehicles) declines. According to the meta-analysis, a doubling of the volumes of pedestrians or cyclists is only expected to increase crashes by 41 %.

Regarding the share of heavy goods vehicles, results are mixed. One study indicates that the impact of HGVs on crash frequency may vary depending on the road type (high or low capacity), one indicates that the percentage of HGVs is not related to crash frequency and the third indicates that crash numbers decrease as the number of HGVs increase, holding car volume constant.

1.3.2 Transferability

With similar results from studies from a variety of countries and several levels of measurement units, the results from the meta-analysis on the safety-in-numbers effect appears to be similar for western countries, and for both urban and rural areas. The available evidence for shares of other road users is limited, with studied on the share of HGVs reaching very different conclusions. Since studies differ with regard to countries, road types, measurement of HGVs and analysis, it remains unclear what is the main source of result differences.

1.3.3 Notes on analysis methods

While the SIN effect is reported across studies and contexts, the studies do not say if this association is due to a) more cyclists *causing* lower risk, b) lower risk causing more cyclists, or c) some other factor, such as infrastructure quality, affecting both cyclist share and risk. More research is needed on the share of HGVs and PTWs to establish how this relates to road safety.

In studies of SIN one can see an improvement in quality over time. Recent studies include more variables and are based on more extensive statistical analyses than the oldest studies. These studies can be regarded as methodologically sound. The picture is less clear as far as HGV studies are concerned.

2. Scientific overview

2.1 LITERATURE REVIEW

2.1.1 On the investigation of safety-in-numbers.

The SIN effect is generally estimated from multivariate crash prediction models including volumes for motor vehicles and pedestrian or cyclists, as well as any additional independent variables (such as type of crossing and speed limit). The resulting estimated regression coefficients indicate the change in crashes associated traffic volume increases, holding other variables in the model constant. If the estimated coefficients for both motor vehicle- and pedestrian (or cyclist) volume are less than one, it is generally concluded that there is a safety-in-numbers effect.

As noted in the summary, it is not clear whether the association identified between the volumes of cyclist, pedestrians and cars and crashes is causal, or if it is explained by confounders such as selective recruitment of road users or infrastructure quality. A number of potential issues related to the investigation and interpretation of the SIN effect ought to be mentioned.

Elvik (2013) argues for a distinction between a complete and a partial safety-in-numbers effect: As mentioned, a coefficient below one is generally interpreted as in accordance with a SIN effect. But if the sum of the coefficients for motor vehicle flow and the flow of cyclists/pedestrians is larger than 1, it may be characterized as a partial SIN, or potentially hazard in numbers. In such instances, the increase in crashes associated with an increase in pedestrian flow could be less than proportional to the volume increase *if the volume of motor vehicles is held constant*. However, if the volumes of cyclists/pedestrians and motor vehicles are positively correlated, there might not be an overall safety-in-numbers effect: When the coefficients sum to more than one, crashes would more than double when the sum of pedestrian and motor vehicle volume doubles (Elvik, 2013).

Several authors have raised the issue that some studies employ a model of the relationship between traffic volume and crashes which give rise to a negative relationship that appears to be a safety-in-numbers effect but may be a statistical artefact (see e.g. Elvik & Bjørnskau, 2015; Elvik, 2013; Knowles et al., 2009). This applies to studies that define risk as (injury/km travelled) and exposure as (km travelled/number of inhabitants), which by definition produces a negative association between exposure and risk that will appear to be a SIN effect. No such studies are included in this synthesis, nor in the meta-analysis of Elvik and Bjørnskau.

Another potential issue is that all models, both in the meta-analysis and two additional studies, specify a monotonic functional relationship for the relationship between traffic volumes and crash frequency. It is, however, possible that such an effect has a limit or a turning point (Elvik, 2009), but this has not been investigated in any of the identified studies.

2.1.2 How could HGV share affect road safety?

The results on the share of HGVs on crash frequencies are mixed, leaving uncertainty regarding how this would affect road safety. In the reviewed studies, several possible mechanisms are proposed: It may be that larger shares of HGVs in some cases reduce the average speed, which in turn affects road safety. On the other hand, HGVs driving slower than light vehicles could increase the speed differences, resulting in a detrimental effect on road safety. It could also be that a higher share of light vehicles corresponds to increases in overtaking manoeuvres using the oncoming lane, producing more possible conflict scenarios and increasing crash risk. Or it could be that the number of HGVs on the road coincides with other factors that affect the crash frequency, such as good road conditions or times of the day when experienced drivers are driving (Hiselius, 2004; Ramirez et al., 2009).

2.2 DESCRIPTION OF STUDIES

Six studies are reviewed, including one meta-analysis. All studies are concerned with crash frequency, and three focus on the shares of HGVs and cars, while the remaining three, including the meta-analysis, investigates the Safety-in-numbers effect related to shares of pedestrians, cyclists and motor vehicles.

2.2.1 How is traffic composition measured?

All models in the meta-analysis, as well as the two original studies coded on safety-in-numbers, are similar; multivariate crash prediction models that estimate regression coefficients for how the number of crashes depend on the conflicting flows (see literature review). For the share of HGVs, multivariate crash prediction models including the percentage of heavy goods vehicles in addition to the total traffic volume (and possibly other control variables) are typically used to estimate the effect on road safety. The studies reviewed here focus on the distribution of crash frequencies over time/segments as dependent variable.

Table 1. Description of sampling frames of coded studies.

Author(s), year, country	Sample, context	Crashes	Road users	Design, analysis
Pedestrians, cyclists and motor vehicles				
Elvik & Bjørnskau, 2015, several	Based on 15 studies investigating the SIN effect on micro (e.g. crossings), meso (e.g. road networks) and macro (e.g. cities) levels, from which 25 coefficients were meta-analysed	Involving both cars and either pedestrians or cyclists	Pedestrians Cyclists Motor vehicles	Inverse-variance meta-analysis with both fixed and random effects
Elvik, 2016, Norway	Police-reported crashes occurring in 239 pedestrian crossings in the larger Oslo area.	Police-reported crashes: collisions between motor vehicle and pedestrian or cyclist	Pedestrians Cyclists Motor vehicles	Negative binomial with log link function.
Kröyer, 2016, Sweden	113 intersections in middle-sized cities in Sweden, with 5 years of accident data (2008-2012), traffic counts	From police- and hospital databases, collisions between motor vehicle and pedestrian or cyclist*	Pedestrians Cyclists Motor vehicles	Negative binomial
Heavy goods vehicles and cars				
Daniel & Maina, 2011, USA	998 freeway segments from New Jersey, one year (2008) of crash- and traffic data.	All crashes.	Cars HGVs	Negative binomial
Hiselius, 2004, Sweden	83 rural road sections, hourly traffic flow per car/lorry from 1989 to the middle of 1995, separated into four road types with different road widths and speed limits	Injury crashes, approximately 160 and 600 crashes for the road type with least and most crashes, respectively	Cars HGVs	Poisson regression

Ramirez et al., 2009, Spain	2541 road segments on interurban roads. AADT per vehicle type. 1 year (2001) of traffic and crash data for model development, validated with 2 more years of crash data.	Injury crashes, police-reported.	Cars HGVs	Negative binomial with log link function

Note: *The study also contains estimates for single bicycle accidents and single pedestrian accidents, which are not relevant for traffic composition (nor SIN, according to Elvik & Bjørnskau, 2015) and will not be addressed here.

Table 1 outlines the sampling frames and methodologies of the coded studies, grouped by road users investigated. All studies use crash frequency as outcome variable, and all original studies are cross-sectional. An overview of control variables can be found in the supporting document.

2.2.2 How well has the effect of traffic composition been studied?

The safety in numbers effect has been investigated by a large number of studies from different countries and on different levels: The meta-analysis found homogeneous results from studies from Canada, United States, Great Britain, Denmark, Sweden, Netherlands, Norway and New Zealand, and similar estimates for study units on a micro-level (e.g. junctions or pedestrian crossings), meso-level (typically street networks or urban traffic zones), and macro-level (municipalities, cities or states), and covered both urban and rural areas. The number of locations covered in the primary studies varies from 105 to 1000, and the numbers of crashes from 27 to 5349. Elvik and Bjørnskau (2015) found no evidence for publication bias. Still, evidence on the mechanisms explaining this association is lacking, although some mechanisms have been suggested. These include changes in expectations and/or the quality of the interactions between the groups of road users.

Regarding heavy goods vehicles, few studies were identified, and more research is needed to disentangle the effects of road types, time periods and other potentially relevant moderators, as well as differences between countries.

2.2.3 Transferability

The SIN effect is confirmed in all studies. Since studies of the SIN effect have been reported from the 1970s until now, and in many countries, this suggests that the effect can be expected to be found at least in Western, highly motorised countries. Whether it applies to low-income countries is less clear.

2.3 OVERVIEW OF RESULTS

2.3.1 Pedestrians, cyclists and motor vehicles

One meta-analysis and two original studies investigating the relationship between flows of pedestrians, cyclists and motor vehicles were coded. All studies use crash prediction models where the outcomes are regression coefficients for the change in crash frequency expected for an increase in conflicting flows. A coefficient below 1 is generally taken to indicate a safety-in-numbers effect. The results are presented in Table 2. All results are in accordance with a safety-in-numbers effect, i.e. the coefficients are lower than 1. Again, this means that the total number of crashes is expected to increase with volume increases, but less than proportional to the volume increase.

The meta-analysis, based 15 studies and a total of 51 coefficients (25 from car volume, 15 for pedestrian volume and 11 for cycle volume), finds consistent results between studies. The summary estimates are close to 0.5 for all traffic volumes which, converted to elasticities, mean that a doubling in the volume of pedestrians or cyclist is expected to increase the number of crashes by 41

% (Elvik & Bjørnskau, 2015). While the coefficients for both studies indicate a SIN effect, this is far greater in the study of Elvik than in the Kröyer study. The bicyclist model of Kröyer (2016) indicates a partial SIN-effect.

Table 2. Results (regression coefficients) from safety-in-numbers studies.

Author, year, country	Level of analysis	Coefficients			Effect (crashes)	Effect (risk)
		Ped	Cyc	MV		
Meta-analysis						
Elvik & Bjørnskau, 2015, several	All	0.499	0.432	0.511	↗	↘
	Micro (e.g. crossings)	0.563	0.479	0.491	↗	↘
	Meso (e.g. road networks)	0.640	0.514	0.428	↗	↘
	Macro (e.g. cities)	0.566	0.369	*	↗	↘
Original studies						
Kröyer, 2016, Sweden	Micro	0.3		0.64	↗	↘
	Micro		0.36	0.71	↗	↘
Elvik, 2016, Norway	Micro	0.066	0.12	0.048	↗	↘

Note: * no results

2.3.2 Heavy goods vehicles and cars

Three coded studies investigated how the share of heavy goods vehicles relates to crash frequency, all are cross-sectional. Two studies use average traffic data (AADT) and address the percentage of heavy goods vehicles (Ramirez et al., 2009; Daniel & Maina, 2011), while Hiselius (2004) analyse hourly traffic volume data with separate indicators for car volume and lorry volume. The main results are displayed in Table 3.

Table 3. Main results of studies addressing share of heavy goods vehicles.

Author, year, country	Analysis	Measure of HGV share	Effect on crash frequency	Explanation	Control variables
Ramirez et al., 2009, Spain	Negative binomial, log link function	ln (% HGV)	↗ ↘	Increased % of HGVs is related to higher crash frequencies on high-capacity roads, and lower crash frequencies on lower capacity roads	Road type; ln(AADT); ln(%HGV); ln(%HGV) per road type
Hiselius, 2004, Sweden	Poisson regression	Ln (hourly HGV volume)	↘	An increasing number of lorries is related to a lower crash frequency independent of the volume of cars. This is found for all crashes, single vehicle crashes and multiple vehicle crashes.	Exposure (number of hours and km each section is studies); volume of cars
Daniel &	Negative	% HGV	-	A higher percentage of trucks is found	section length; AADT;

Maina, 2011, USA	binomial			to be associated with a higher number of crashes, but the result is not statistically significant.	speed limit; number of lanes; lane width; shoulder width; ramp density

Due to differences in measurement and model architecture, as well as the fact that one study found opposite effects for different road types and it was not evident how these roadtypes were best compared to those investigated in other studies, a meta-analysis was not feasible.

The results are mixed. In the Spanish study, the effect of HGV share on road safety varies by road type. The Swedish study investigated several road types jointly, and the U.S. study found the effect of HGV share not to be significantly related to crash frequency. With the number of studies being low, it is not possible to say for certain if these differences reflect differences between countries, road types, time periods or the design or analysis of the data.

CONCLUSION

One meta-analysis and five original studies investigating the impact of traffic composition on crash occurrence have been coded summarized. Studies on shares of pedestrians, cyclists and cars, including one meta-analysis, consistently find a safety-in-numbers effect: as the volumes of cyclists/pedestrian increases, crashes increase less than proportional to the volume increase. However, this might not always hold if the volume of motor vehicles increases too, and the cause of the association is not known with certainty. The effect of HGV share on road safety is unclear, and more research is needed on this topic.

3. Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature search was conducted in Science Direct, TRID, Springer Link and Taylor & Francis. Additionally, Google Scholar was searched for relevant articles published after the meta-analysis identified. The search was limited to journal articles and reports published after 1999 in the English language. Preliminary searches indicated that search terms such as "traffic composition" returned irrelevant and unmanageable numbers of hits in most databases. Thus, safety in numbers was used as a key search term.

Database: Science Direct **Date:** 16th of March 2016

search no.	search terms / operators / combined queries	hits
#1	TITLE-ABSTR-KEY("safety in numbers") AND (accident* OR crash* OR risk OR safety) AND (pedestrian* OR cyclist* OR bicycl* OR vehicl*)	33
#2	"vehicle mix" AND (accident* OR crash* Or risk OR safety OR injur*)	241

Database: Google Scholar **Date:** 17th of March 2016

search no.	search terms / operators / combined queries	hits
#1	"safety in numbers" AND "accident* OR crash* OR injur* OR risk OR safety) AND (pedestrian* OR vehicle* OR PTW OR cyclist* OR bicycl*)	1020
#2	"safety in numbers" AND (accident* OR safety OR risk OR injur* OR crash*) [years 2015-2016; after meta-analysis]	366

Database: Taylor & Francis **Date:** 16th of March 2016

search no.	search terms / operators / combined queries	hits
#1	("safety in numbers") AND (accident* OR crash* OR risk OR safety) AND (road OR traffic OR transport* OR travel) AND (pedestrian* OR cyclist* OR bicycl* OR vehicl*) NOT(nurse OR patient* OR nursing OR -nursing OR medication*)	125

Database: TRID **Date:** 16th of March 2016

search no.	search terms / operators / combined queries	hits
#1	Keywords: "traffic composition" AND (risk OR accident* OR crash* OR safety)	439

Database: Springer Link **Date:** 11th of March 2016

search no.	search terms / operators / combined queries	hits
#1	("safety in numbers") AND (accident* OR crash* OR risk OR safety) AND (road OR traffic OR transport* OR travel) AND (pedestrian* OR cyclist* OR bicycl* OR vehicl*) NOT(nurse OR patient* OR nursing OR -nursing OR medication*)	136

3.1.2 Results of literature search, screening and prioritizing

After screening titles and abstracts of the search hits, 17 studies were retrieved and screened full-text.
The following elimination criteria were applied:

- Included in the meta-analysis identified
- Result may be statistical artefact (risk is defined as (injury/km travelled) and exposure as (km travelled/number of inhabitants), see literature review section for explanation)
- Share of road users not reported
- Results are not based on accidents/incidents
- Not peer-reviewed

Additionally, since single vehicle crashes are generally not considered to be affected by SIN, results for single vehicle crashes, as well as analyses based on both cyclist/motor vehicle and single crashes were excluded. Such studies were only retained if analyses on crashes that were not single crashes were reported. Furthermore, when multiple studies were based on (mostly) the same data, the study with the larger sampling frame was given priority.

In prioritizing remaining studies, those not compatible with coding (e.g. unusual analyses, insufficient reporting of detail) were given a lower priority. As were studies mostly concerned with different types of road design for mixed traffic.

This left 6 studies to code, including the meta-analysis, which is based on 15 studies (with 8 additional studies excluded).

3.2 LISTS OF STUDIES CONSIDERED AND CODED

Coded studies:

Daniel, J. R., & Maina, E. (2011). Relating Safety and Capacity on Urban Freeways. Procedia - Social and Behavioral Sciences, 16, 317–328. http://doi.org/10.1016/j.sbspro.2011.04.453

Elvik, R. (2016) Safety-in-numbers: Estimates based on a sample of pedestrian crossings in Norway. Accident Analysis & Prevention, 91, 175–182.

Elvik, R., & Bjørnskau, T. (2015). Safety-in-numbers: A systematic review and meta-analysis of evidence. Safety Science, in press.

Kröyer, H. R. G. (2016) Pedestrian and bicyclist flows in accident modelling at intersections. Influence of the length of the observational period. Safety Science, 82, 315–324.

Ramírez, B. A., Izquierdo, F. A., Fernández, C. G., & Méndez, A. G. (2009). The influence of heavy goods vehicle traffic on accidents on different types of Spanish interurban roads. Accident Analysis and Prevention, 41(1), 15–24.

Hiselius, L. (2004). Estimating the relationship between accident frequency and homogeneous and inhomogeneous traffic flows. Accident Analysis and Prevention, 36, 985-992.

Studies screened and rejected based on abovementioned criteria

Clabaux, N., Fournier, J.-Y., & Michel, J.-E. (2014). Powered two-wheeler drivers' crash risk associated with the use of bus lanes. Accident Analysis and Prevention, 71, 306–10.

Elvik, R. (2013). Can a safety-in-numbers effect and a hazard-in-numbers effect co-exist in the same data? Accident Analysis and Prevention, 60, 57–63.

Murphy, B., & Levinson, D. (2015). Evaluating the "Safety In Numbers" Effect With Estimated Pedestrian Activity.

Strauss, J., Miranda-Moreno, L. F., & Morency, P. (2013). Cyclist activity and injury risk analysis at signalized intersections: A Bayesian modelling approach. Accident Analysis and Prevention, 59, 9–17.

Vlahogianni, E. I. (2007). Some empirical relations between travel speed, traffic volume and traffic composition in urban arterials. IATSS Research, 31(1), 110–119.

Wegman, F., Zhang, F., & Dijkstra, A. (2012). How to make more cycling good for road safety? Accident Analysis & Prevention, 44(1), 19–29.

Studies not coded based on inclusion in (or exclusion from) meta-analysis:

Included in meta-analysis:

Brüde, U., & Larsson, J., (1993). Models for predicting accidents at junctions where pedestrians and cyclists are involved. How well do they fit? Accident Analysis & Prevention, 25(5), 499-509.

Buch, T. S., & Jensen, S. U., (2013). Trafikksikkerhed i kryds med dobbeltrettede cykelstier. (Rapportudkast). Lyngby: Trafitec.

Elvik, R., Sørensen, M. W. J., & Nævestad, T.-O , (2013). Factors influencing safety in a sample of marked pedestrian crossings selected for safety inspections in the city of Oslo. Accident Analysis & Prevention, 59(0), 64-70.

Geyer, J., Raford, N., Ragland, D., & Pham, T., (2006). The Continuing Debate about Safety in Numbers—Data from Oakland, CA. TRB annual meeting CD-ROM

Hall, R.D., (1986). Accidents at four-arm single carriageway urban traffic signals. Contractor Report 65. Transport and Road Research Laboratory, Crowthorne, Berkshire

Harwood, D. W., Torbid, D. J., Gilmore, D. K., Bokenkroger, C. D., Dunn, J. M., Zegeer, C. C., … Persaud, B. N., (2008). Pedestrian Safety Prediction Methodology. NCHRP Web-only Document 129 Phase III. Washington DC.: Transportation Research Board.

Inwood, J., Grayson, G.B., (1979). The comparative safety of pedestrian crossings. TRRL Laboratory Report 895. Transport and Road Research Laboratory, Crowthorne, Berkshire

Jonsson, T., (2005). Predictive models for accidents on urban links - A focus on vulnerable road users. PhD, Lund University, Lund. (Bulletin 226)

Leden, L., (2002). Pedestrian risk decrease with pedestrian flow. A case study based on data from signalized intersections in Hamilton, Ontario. Accident Analysis & Prevention, 34(4), 457-464.

Lyon, C., & Persaud, B. N., (2002). Pedestrian Collision Models for Urban Intersections. Transportation Research Record 1818

L.F. Miranda-Moreno, J. Strauss, P. Morency, (2011). Disaggregate exposure measures and injury frequency models of cyclist safety at signalized intersections. Transp. Res. Rec., 2236 (2011), pp. 74–82

Nordback, K., Marshall, W. E., & Janson, B. E., (2013). Bicyclist safety performance functions for a US city. Paper presented at the TRB Annual Meeting, Washington DC

Prato, C.G., Kaplan, S., Rasmussen, T.K., Hels, T., (2014). Infrastructure and spatial effects on the frequency of cyclist-motorist collisions in the Copenhagen region. Artikler fra Trafikdage på Aalborg Universitet. ISSN 1603-9696

Schepers, J. P., & Heinen, E., (2013). How does a modal shift from short car trips to cycling affect road safety? Accident Analysis & Prevention, 50(0), 1118-1127.

J.P. Schepers, P.A. Kroeze, W. Sweers, J.C. Wüst, (2011). Road factors and bicycle-motor vehicle crashes at unsignalized priority intersections. Accid. Anal. Prev., 43 (2011), pp. 853–861

Summersgill, I., Layfield, R.E., (1996). Non-junction accidents on urban single-carriageway roads.

Turner, S. A., Roozenburg, A. P., & Francis, T., (2006). Predicting Accident Rates for Cyclists and Pedestrians. Land Transport New Zealand Research Report 289. Wellington: Land Transport New Zealand

Zegeer, C. V., Stewart, J. R., Huang, H. H., Lagerwey, P. A., Feaganes, J., & Campbell, B. J., (2005). Safety effects of marked versus unmarked crosswalks at uncontrolled locations: final report and recommended guidelines. Washington DC: Federal Highway Administration

Excluded from meta-analysis: Statistical relationship may be an artefact

Jacobsen, P. L., (2003). Safety in numbers: more walkers and bicyclists, safer walking and bicycling. Injury Prevention, 9(3), 205-209.

Knowles, J., Adams, S., Cuerden, R., Savill, T., Reid, S., & Tight, M., (2009).

Technical Annex to PPR445 Collisions involving pedal cyclists on Britain's roads: establishing the causes. Wokingham: Transport Research Laboratory

Robinson, D. L., (2005). Safety in numbers in Australia: more walkers and bicyclists, safer walking and cycling. Health Promotion Journal Australia 16(1), 47-51.

Vandenbulcke, G., Thomas, I., de Geus, B., Degraeuwe, B., Torfs, R., Meeusen, R., & Int Panis, L., (2009). Mapping bicycle use and the risk of accidents for commuters who cycle to work in Belgium. Transport Policy, 16(2), 77-87

Excluded from meta-analysis: Contains data on cyclist volume only

Bonham, J., Cathcart, S., Petkov, J., & Lumb, P., (2006). Safety in numbers: a strategy for cycling. Australasian Transport Research Forum (ATRF), 29, 9

Leden, L., Gårder, P., Pulkkinen, U., (1998). Measuring the safety of raised bicycle crossings using a new research methodology. Paper presented at the Transportation Research Board Annual Meeting, Washington DC

Schepers, P., (2012). Does more cycling also reduce the risk of single-bicycle crashes? Injury Prev., 18 (2012), pp. 240–245

Excluded from meta-analysis: States coefficient only for cross-product of flows; not for cars and pedestrians

Maycock, G., Hall, R.D., (1984). Accidents at 4-arm roundabouts. TRRL Laboratory Report 1120. Transport and Road Research Laboratory, Crowthorne, Berkshire.

Additional References

Elvik, R., (2009). The non-linearity of risk and the promotion of environmentally sustainable transport. Accident Analysis and Prevention, 41, 849–855

Elvik, R. (2013). Can a safety-in-numbers effect and a hazard-in-numbers effect co-exist in the same data? Accident Analysis and Prevention, 60, 57–63.

Knowles, J., Adams, S., Cuerden, R., Savill, T., Reid, S., Tight, M., (2009). Technical Annex to PPR445 Collisions Involving Pedal Cyclists on Britain's Roads: Establishing the Causes. Transport Research Laboratory, Wokingham.

Synopsis 5: Risks associated with the distribution of traffic flow over arms at junctions

1 Summary

Papazikou E., September 2016

COLOUR CODE: GREY

There was adequate number of studies investigating the risk factor of distribution of traffic flow over arms at junctions, but distribution of flow over arms at junctions was rarely the main variable of interest included in the crash models. Furthermore, the risk factor is not expressed in a consistent way across the studies, resulting in an unclear picture of its overall effect.

KEYWORDS: Distribution of traffic flow, traffic volume split, junction arms, secondary road, primary road, major road, minor road, turning lanes.

1.1 ABSTRACT

In the case where primary and secondary roads converge, the distribution of traffic flow over the arms of a junction can introduce a non-trivial risk. In general, it is not easy to make a clear conclusion about the effect of the distribution of traffic flow over the arms of a junction. This is due to the different variables that the different studies used to express the specific risk factor. In situations where there is an increase to: (i) the traffic on the minor or major road, (ii) the ratio of major road traffic to the minor road traffic or (iii) the number of turn lanes, crash frequency tends to increase. On the contrary, when there is a high flow imbalance between the junction branches, the number of crashes reduces. Crash severity also increases with an increase in the major road's Annual Average Daily Traffic (AADT). Finally, the SafetyCube meta-analysis showed that the amount of traffic flow of the secondary road of a junction can result in an increase in the number of crashes at a 95% confidence level.

1.2 BACKGROUND

1.2.1 Definitions of traffic distribution over arms at junctions

There is no specific definition for this risk factor; interpretation varies between studies. Traffic distribution over arms at junctions refers to the traffic split across the branches of a junction or the traffic volumes on the major vs the minor road and it is usually expressed as ADT (Average Daily Traffic). For example, when two roads converge at a junction, each road may have a different traffic flow. The difference between these, at the point the roads converge, is considered the distribution of traffic flow over arms of junctions. This is particularly a problem when a primary and a secondary road converge.

1.2.2 How does the distribution of flow over arms at junctions affect road safety?

Generally, the effect of traffic flow is critical in crash frequency and severity. The way that the traffic volumes are split over the different branches of a junction can also affect road safety as it influences the driving time and complexity. A traffic flow imbalance between the approaches of different roads (particularly when a major and minor road converge), the number of turning lanes and a difference between the major and minor road's traffic volume can result in significant change of crash occurrence and severity.

1.2.3 Which safety outcomes are affected by traffic distribution over arms at junctions?

In the coded studies, the effect of traffic distribution over arms at junctions on road safety has been investigated using crash frequency (number of crashes) and crash severity (severity of injuries of occupants given that a crash has occurred).

1.2.4 How is the effect of distribution of flow over arms at junctions studied?

As distribution of flow over arms at junctions constitutes a very specific risk, usually absorbed from the total entering traffic volumes in a junction, this overview gathers 8 studies from Europe and America. The studies employ models with multiple explanatory variables and the distribution of flow is examined in several forms e.g. natural logarithm of AADT on the major road, ratio of major road AADT to minor road AADT, flows on the approach streets of an intersection, ratio of the minor approach traffic volume to the major approach traffic volume, incoming motor vehicle traffic from the primary and secondary direction, percentage of minor road traffic and minor approach right-turn lanes traffic volume. The relationship between the split of traffic volumes and the number of crashes is investigated by Poisson and negative binomial models whereas the study employed the crash severity model applied binary probit framework.

1.3 OVERVIEW OF RESULTS

While most studies used multivariate methods to estimate the effect of distribution of flow over arms at junctions, the distributions used and the included variables differ considerably and the risk factor expressed with different variables in most of the studies, rendered a meta-analysis of results really difficult. Nevertheless, a successful attempt was made to apply a meta-analysis on 3 arm and 4 arm junctions regarding the secondary road traffic flow and crash frequency. Finally, 2 meta-analysis were completed, one random effects meta-analysis for 3 arm junctions and one fixed effects meta-analysis for 4 arm junctions.

The results of the meta-analysis suggest that a higher traffic volume of a secondary joining road leads to a significant increase in crash frequency for both 3 and 4 arm junctions and at a 95% confidence level. Concerning crash frequency, the estimate of the elasticity for 3 arm junctions was 0.396 (p-value = 0.0004) and for 4 arm junctions was 0.480(p-value<0.0001). The forest plots for the estimates are presented in the Scientific Overview.

1.4 NOTES ON ANALYSIS METHODS

The studies considered are methodologically strong. However, distribution of flow over arms at junctions was never examined separately and exclusively, but it was one of the many variables included into several multivariate models. Therefore, the topic has not been investigated in-depth. Nevertheless, the applied methods are quite consistent as there are crash frequency models with similar controlling variables. There is a necessity for more studies on crash severity though, as only one was coded. Moreover, there are not many European studies and the risk factor has not been tested for different road user groups. In summary, although the methods used are consistent, the effect is not very clear due to the different variables used to express the same risk factor.

2 Scientific overview

2.1 DESCRIPTION OF AVAILABLE STUDIES

2.1.1 Literature review

Golias (1992) tried to establish relationships between the expected number of crashes and the flows of the traffic streams passing through a junction. The main conclusion of the study was that the dominant factor influencing the crash potential of an urban junction is an expression of the interacting traffic stream flows. Greibe (2003) developed crash prediction models for junctions taking in to consideration the traffic flow of major and minor road and stated that motor vehicle traffic volume was the most significant variable. More specifically, Ferreira and Couto (2013) reported that when the difference between major and minor traffic volume increases or decreases, the crash risk is expected to change significantly. This is supported by another study that proved that a higher imbalance in traffic flow is connected with a lower crash propensity (Castro et al., 2012). Agbelie & Roshandeh (2015) examined the ratio of traffic volume on the major road to this on the minor road and proved that as this ratio increases, the crash frequency also increases. The minor's road traffic increase has the same effect to crash rate, too (Kulmala, 1995).

The number of crashes at intersections seems to be also associated with the number of right turning lanes on minor street approaches (Pulugurtha and Nujjetty, 2011), as well as, with the left turning traffic flow on the major approach (Guo et al., 2010).

2.1.2 Analysis of study designs and methods

8 studies were coded. 7 of them examined crash frequency while 1 investigated crash severity. All the studies have employed multivariate statistical models as an approach to the topic and tried to control for several junction characteristics including the traffic split over their arms. 5 of the studies are based on data from USA (Florida, North Carolina, Illinois, Texas), one from Brazil and only 2 from Europe (Finland and Denmark).

The one study that examined crash severity developed a binary probit model and states that as the natural logarithm of AADT on the major road increases, the severe injury probability reduces. All the others used generalized linear models to investigate the effect of different variables on crash frequency. **Table 3** and **Table 4**, in the Supporting document, present the main features and outcomes of the coded studies respectively.

2.2 ANALYSIS METHODS AND RESULTS

2.2.1 Introduction

The effect of the differences between traffic flow distribution on 2 or more converging arms at a junction has been identified can be summarized as follows:

- 1 study with a significant decrease in the number of crashes (when the flow imbalance is higher)
- 5 studies with a significant increase in the number of crashes (when there is an increase to: the minor or major road traffic, the number of turning lanes, the ratio of major road traffic to the minor road traffic)
- 1 study that presents a positive and two negative effects on road safety (major road through-traffic, major road left turn-traffic, minor road through-traffic)
- 1 study with a weak decrease in crash severity (at a 90% level), (when the natural logarithm of AADT on the major road increases)

Here it should be noted that the risk factor of distribution of traffic flow over arms at junctions presents a peculiarity as there is no fixed variable to be used in every study. Therefore, any studies that refer to the imbalance of traffic flows between the branches of a junction or the primary or secondary road traffic are taken into consideration.

2.2.2 Transferability

Based on the studies that have been coded, the risk factor of distribution of flow over arms at junctions has not been investigated under a broad range of conditions. All the studies use regional data and most of them are from U.S.A. Moreover, the majority of them refer to urban environment and have not looked at different road users. The effect of distribution of flow over arms at junctions is confirmed in the studies, but there are many different variables included that affect the final result every time (region, number of turning lanes, movements, lighting conditions, etc.). Therefore, the transferability of the results is not high.

2.3 META-ANALYSIS FOR THE SECONDARY ROAD TRAFFIC (flow entering a junction from the minor road when a major and a minor road converge)

A meta-analysis has been carried out in order to find the overall estimate of traffic flow distribution over arms at junctions on crash frequency. More specifically, the minor road's traffic for 3 arm and 4 arm junctions was examined for this analysis. The reasons for this decision are that:

a) A minimum required number of effects for each type of junction is achieved (3). It should be mentioned here that two effects were taken from the same paper.
b) Studies used the same model specifications (Poisson distribution)
c) The sampling frames were similar
d) The measure of effect was the same (elasticity)

The results of the meta-analysis suggest a significant negative effect of secondary road traffic at junctions on road safety (both for 3 and 4 arm junctions) at a 95% confidence level. This is translated to an increase on crash number. **Figures 1 and 2** present the forest plots for the estimates of elasticity.

Figure 1 Forest plot for 3 arm junctions

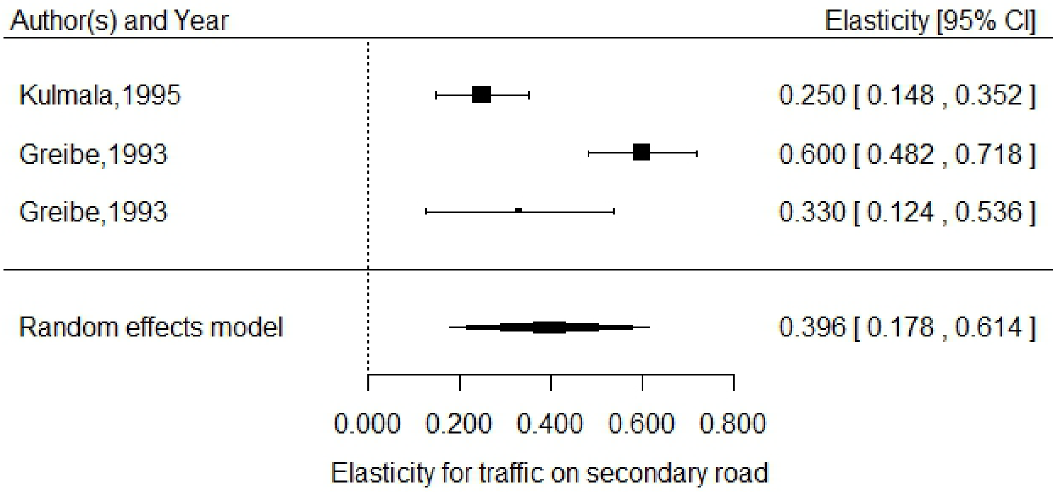
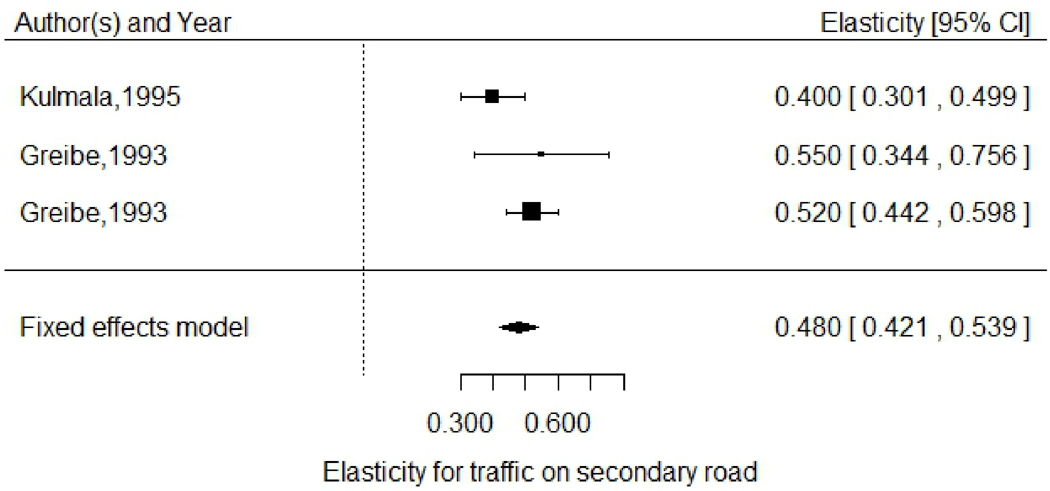


Figure 2 Forest plot for 4 arm junctions



2.3.1 Overall estimate for secondary road traffic at 3-arm junctions on crash frequency

Results of the random-effects meta-analysis indicate that the overall estimate of the effect of secondary road traffic flow at junctions on crash frequency and for 3 arm junctions is 0.396, while the 95% confidence intervals are 0.1775 and 0.6142 (**Table 2**). The p-value (0.0006) indicates a significant effect referring to an increase in the number of crashes.

Table 1 Random effects meta-analysis for secondary road traffic flow at 3-arm junctions on crash frequency.

Variable	Unit	Estimate	Std. Error	p-value	95% CI
Secondary road traffic flow	ADT	0.396	0.1114	0.0004	(0.1775, 0.6142)

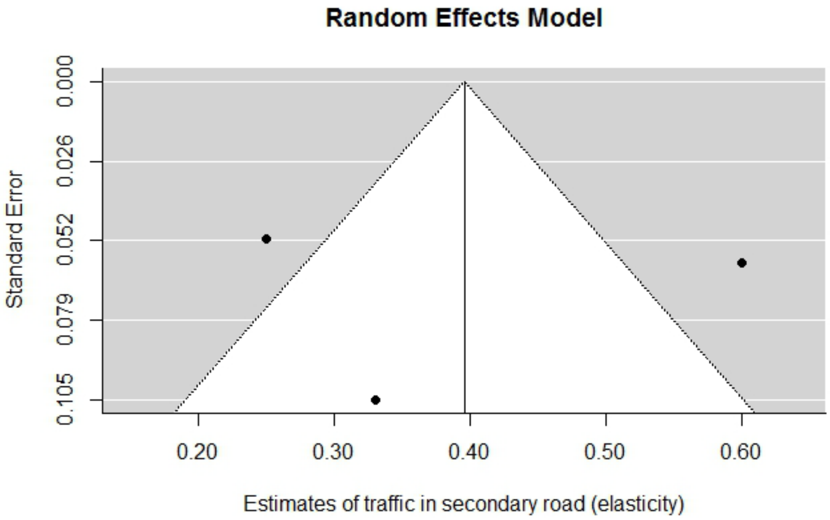
2.3.2 Heterogeneity

The Q test is significant (Q= 19.8804, p-value<0.0001) suggesting that considerable heterogeneity exists among the true effects. As I^2 indicates, 87.46% of the total variability in the effect size estimates can be attributed to heterogeneity among the true effects.

2.3.3 Publication Bias

A funnel plot was firstly produced in order to detect potential publication bias. No publication bias seems to exist. The regression test for funnel plot asymmetry was not significant at a 95% level (p-value = 0.9429), suggesting no existence of publication bias.

Figure 3 Funnel Plot for crash frequency (effect of secondary road traffic at 3-arm junctions).



2.3.4 Overall estimate for secondary road traffic at 4-arm junctions on crash frequency

Results of the random-effects meta-analysis indicate that the overall estimate of the effect of the traffic on secondary road at 4-arm junctions on crash frequency is 0.480, while the 95% confidence intervals are 0.4212 and 0.5390 (**Table 3**). The p-value (<0.0001) indicates a statistically significant increase in crashes.

Table 2 Random effects meta-analysis for secondary road traffic flow at 4-arm junctions on crash frequency.

Variable	Unit	Estimate	Std. Error	p-value	95% CI
Secondary road traffic flow	ADT	0.480	0.0301	<0.0001	(0.4212, 0.5390)

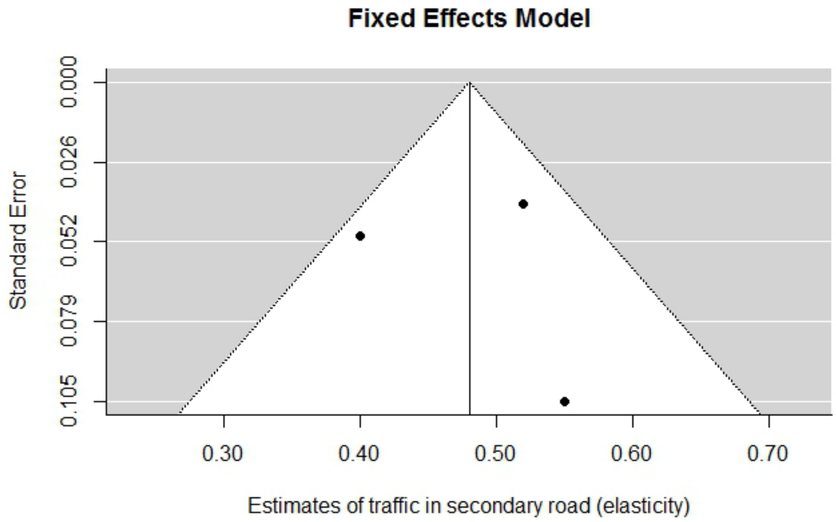
2.3.5 Heterogeneity

The Q test is not significant (Q= 3.9441, p-value=0.1392) indicating that there is not considerable heterogeneity among the true effects.

2.3.6 Publication Bias

A funnel plot was firstly produced in order to detect potential publication bias. No publication bias seems to exist. The regression test for funnel plot asymmetry was not significant at a 95% level (p-value = 0.9554), therefore the effects did not show presence of publication bias.

Figure 4 Funnel Plot for crash frequency (effect of secondary road traffic at 4-arm junctions).



2.3.7 Conclusion

The risk factor examined here is a special case where the relevant variables, used in different studies to express it, differ. This synopsis includes studies that suggest an unequal traffic flow between the branches of a junction or studies examining the effect of increasing or decreasing flow of the major or minor road in a junction. The analysis of the studies showed that the difference in traffic flows between the arms of a junction has a significant effect on road safety. More specifically and considering the meta-analysis results, the increase on secondary road traffic flow, could lead to a significant increase in the number of crashes.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The search strategy focused on identifying the most relevant and recent studies in order to investigate the effect of the examined risk factor. Two data bases were searched for recent literature on the risk of distribution of traffic flow over arms at junctions.

<u>Scopus</u>

First of all, the searches for all the queries were limited to Title-abstract-keywords. The asterisk(*) and W/4(within 4 words) were used in order for more studies to be picked up and queries were combined in advanced search. After the first search, filters were put on the results. Papers before 1990 were excluded and at the Subject area papers from Biochemistry, Genetics and Molecular Biology, Neuroscience, Pharmacology, Toxicology and Pharmaceutics, Chemistry, Physics and Astronomy were also subtracted from the results. Therefore, from 285 initial papers, 202 remained on Scopus.

Database: Scopus **Date:** 1st April 2016

search no.	search terms / operators	hits
#1	traffic W/4 volume* OR traffic W/4 flow* OR traffic W/4 distribution OR vehicle* W/4 volume* OR vehicle* W/4 flow* OR vehicle* W/4 distribution	58,178
#2	"junction*" OR "intersection*" OR "roundabout*"	390,730
#3	"road safety" OR "crash*" OR "accident*" OR "collision*" OR "incident*"	1,001,801
#4	"risk* OR "severity" OR "frequency"	5,838,450
#1 AND #2 AND #3 AND #4	All years	285
After limitations/exclusions	After 1990	**202**

<u>TRID</u>

TRID is not so flexible to use, so the suitable queries should be created carefully and be combined. It is preferable to put the filter (e.g. before 1990) before each query search as afterwards it is not possible. After this process, 22 papers remained.

Database: TRID (trid.trb.org) **Date:** 11th April 2016

search no.	search terms / operators	hits
#1	"distribution of flow" or "distribution of traffic flow"	246
#2	vehicle* distribution or flow* distribution	15000
#3	"junction*" OR "intersection*" OR "roundabout*"	15000
#4	"road safety" OR "crash*" OR "accident*" OR "collision*" OR "incident*"	15000
#5	"risk* OR "severity" OR "frequency"	15000
#1 OR #2 **(referred to as #6)**		15005
#6 AND #3 AND #4 AND #5	All years	**22**

Totally, 224 papers (202 from Scopus and 22 from TRID) were screened (title and abstract). The risk factor was so specific that usually a full text screening was needed in order to identify if a paper was really relevant. Finally, 137 studies seemed to be irrelevant with the topic and 53 were not clear. We made the decision to start prioritising the studies that are clearly more relevant, so we completed a full text examination of **35** papers. The most important criteria that was used for prioritisation was the relevance with the risk factor.

Finally, following the criteria of relevance with the topic (if a paper indicates the distribution of junction flows as a risk factor), 9 papers are considered for the synopsis and 8 of them have been coded. The one paper that was not coded provides information about the specific risk factor but no statistical evidence.

3.2 ANALYSIS OF STUDY DESIGNS AND METHODS

Below **Table 3** presents the main features of the coded studies (author, country, method, risk factor examined and measure of effect) on distribution of flow over arms at junctions while **Table 4** gathers information on the main outcomes (outcome variable, effect on road safety and main outcome).

Table 3 Description of coded studies

Author, year, country	Country	Risk factor	Method	Measure of effect
Greibe P., 2003	Denmark	Traffic flow on primary and secondary road	Generalized linear model- Poisson distribution	**elasticity**
Kulmala, 1995	Finland	Percentage of minor road traffic and overall traffic flow	Generalized linear model- negative binomial distribution	**elasticity**

Author, year, country	**Country**	**Risk factor**	**Method**	**Measure of effect**
Castro, M., Paleti, R., Bhat, C.R., 2012	USA, Texas	Flows on the approach streets for each intersection	Generalized ordered-response model	**elasticity**
Pulugurtha S. and Nujjetty A., 2011	USA, North Carolina	Minor approach right-turn lanes	Generalized linear model- Negative binomial distribution	**correlation coefficient**
Guo F., Wang X., Abdel-Aty M., 2010	USA, Florida	ADT of each intersection approach: ADT per lane through-traffic on major road, ADT per lane left-turn traffic on major road, ADT per lane through-traffic on minor road Signalised junctions	Bayesian models (Poisson CAR model)	**slope**
Ferreira,S., Couto, A., 2013	Brazil	Ratio of the minor approach traffic volume to the major approach traffic volume Signalised junctions	Random-effect Poisson model	**slope**
Agbelie, B. & Roshandeh, A., 2015	USA, Illinois	Ratio of major road AADT to minor road AADT Signalised junctions	a random-parameters negative binomial model.	**marginal effect**
Haleem, K., Abdel-Aty, M., 2010	USA, Florida	The annual average daily traffic (AADT) on the major road unsignalised junctions	Binary probit model	**percent change and marginal effect**

Table 4 Main outcomes of coded studies

Author, year, country	Outcome variable	Effects for Road Safety*	Main outcome -description
Greibe P., 2003	Crash frequency (number of crashes)	Negative	Models that relate the crash occurrence with the traffic flow and road design (95% confidence level)
Kulmala, 1995	Crash frequency(number of crashes)	Negative	As the minor road's portion of traffic increases, the crash rate increases (95% confidence level)
Castro, M., Paleti, R., Bhat, C.R., 2012	Crash frequency(number of crashes per year at each intersection)	Positive	A lower crash propensity associated with higher flow imbalance. (No confidence level)
Pulugurtha S. and Nujjetty A., 2011	Crash frequency (number of crashes)	Negative	The number of turn lanes generally tend to increase the number of crashes at an intersection (95% confidence level)
Guo F., Wang X., Abdel-Aty M., 2010	Crash frequency (number of crashes)	Positive, negative, negative	• for one standardized unit of increase in major through-traffic (3000 vehicles per lane, i.e., one standard deviation), the expected crash rate as measured by the number of crashes per thousand vehicles will drop by a multiplicative factor of exp(−0.18) = 0.83. • with one unit increase (1000 vehicles per day) the crash rate will increase by a factor of exp(0.2) = 1.22(left-turn) • with one unit increase for through-traffic per lane on minor roads (equivalent to 2200 vehicles per day), the crash rate will increase by a factor of exp(0.18) = 1.2. • (95% confidence level)
Ferreira,S., Couto, A., 2013	Crash frequency (number of crashes)	Negative	when F2/F1 approaching 0 the crash risk is high; when the difference between major and minor traffic volume increases or decreases, the crash risk is expected to change significantly
Agbelie, B. & Roshandeh, A., 2015	Crash frequency (number of crashes)	Negative	For most of the intersections, increasing the ratio of traffic volume on the major road to this on the minor road will increase crash frequency. A unit increase in this ratio would increase crash frequency by 1.32. (no confidence level).
Haleem, K., Abdel-Aty, M., 2010	Crash Severity	Positive	As the natural logarithm of AADT on the major road increases, the severe injury probability reduces. (90% confidence level).

* **Negative**: increase crash number/severity, **Positive:** decrease crash number/severity

3.3 LIST OF CODED AND CONSIDERED PAPERS

3.3.1 Coded papers

1. Greibe, P. (2003). Accident prediction models for urban roads. *Accident Analysis & Prevention*, *35*(2), 273–285. doi:10.1016/S0001-4575(02)00005-2
2. Kulmala, R. (1996). Safety at rural three- and four-arm junctions. Development and application of accident prediction models. *VTT Publications*, (233). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-13844323897&partnerID=tZOtx3y1
3. Haleem, K., & Abdel-Aty, M. (2010). Examining traffic crash injury severity at unsignalized intersections. *Journal of Safety Research*, *41*(4), 347–357. doi:10.1016/j.jsr.2010.04.006
4. Pulugurtha, S. S., & Nujjetty, A. P. (2011). Crash Estimation Models for Intersections. In Transportation and Development Institute Congress 2011 (pp. 1306–1314). Reston, VA: American Society of Civil Engineers. doi:10.1061/41167(398)124
5. Agbelie R D K, B., Roshandeh M, A., Agbelie, B. R. D. K., & Roshandeh, A. M. (2015). Impacts of Signal-Related Characteristics on Crash Frequency at Urban Signalized Intersections. Journal of Transportation Safety & Security, 7(3), pp 199–207. doi:10.1080/19439962.2014.943867
6. Ferreira, S., & Couto, A. (2013). Traffic flow-accidents relationship for urban intersections on the basis of the translog function. Safety Science, 60, 115–122. doi:10.1016/j.ssci.2013.07.007
7. Castro, M., Paleti, R., & Bhat, C. R. (2012). A latent variable representation of count data models to accommodate spatial and temporal dependence: Application to predicting crash frequency at intersections. *Transportation Research Part B: Methodological*, *46*(1), 253–272. doi:10.1016/j.trb.2011.09.007
8. Guo, F., Wang, X., & Abdel-Aty, M. A. (2010). Modeling signalized intersection safety with corridor-level spatial correlations. *Accident Analysis and Prevention*, *42*(1), 84–92. doi:10.1016/j.aap.2009.07.005

3.3.2 Considered papers

1. Golias, J. C. (1992). Establishing relationships between accidents and flows at urban priority road junctions. *Accident Analysis and Prevention*, *24*(6), 689–694. doi:10.1016/0001-4575(92)90023-C

Synopsis 6: Risk of Different Road Types

1 Summary

Quigley C, September 2016

Colour Code: Yellow

Limited international literature indicates that, when all road users are considered together, the "higher" the road type/class is, the greater the crash and injury frequency will be and the higher the risk of severe injuries will be. This could in part be due to structural variations across road types in terms of the presence of other known risk factors (e.g. number of lanes, traffic volume, traffic composition...). However, not all literature highlighted statistically significant results and the road type/class categories used in the studies varied, so had to be grouped in the overall analysis (e.g. motorways grouped with other major arterial roads), leading to potentially over-generalised results.

Keywords

Road functional class; road type; road type categorisation; crash risk; injury risk; injury severity.

1.1 ABSTRACT

For most countries, road are generally organised into classes which reflect the main function and traffic type they are designed for and this is described as road functional class, or in general, road type. In the literature analysed, all road types were considered from minor local roads to major arterial roads and motorways, but the categorisation used varied across each country and study, which made road type a complicated topic to analyse. Studies used either crash frequency (and in one case, crash rate), casualty frequency or injury severity as a measure of the risk of road types. It was found that overall, minor roads were statistically significantly safer than major roads in terms of both crash and casualty frequency and also injury severity. This result was reversed when examining particular cases (e.g. collisions only involving tractor-trailers). However, not all studies were statistically significant and the overall results may be generalised due to having to group road type categories across studies to allow a cross-study analysis to be made.

1.2 BACKGROUND

1.2.1 What is road type?

Road type is a general term for classifying or categorising roads and can include the characteristics of the road as well as its function (e.g. 2+1 road, residential road...). In most countries, roads are generally organised into classes which reflect the main function and traffic type they are designed for (e.g. high speed roads allowing motorised traffic to travel from one location in a country to another). Each country has their own road class system. A good example is in the USA, where there are three main classes of roads, these being ***arterial roads*** (mainly high speed roads for mobility and long-distance travel across the country, states regions and cities) ***collector roads*** (roads which link the arterial roads to the local roads and vice versa and are used by local transport services) and ***local roads*** (low speed roads not intended for through travel, often at the start/end of a journey and frequently used by vulnerable road users) (US Department of Transportation, 2013).

1.2.2 How does road type affect road safety?

Not classifying a road appropriately in terms of its function can potentially increase the likelihood of collision occurring. For example, if a high-speed arterial road was introduced in a location used frequently by pedestrians and cyclists, the risk of a collision between high speed vehicles and vulnerable road users would be increased. So it is important to determine whether the "right" road is in the "right" place in terms of its function.

1.2.3 Which safety outcomes are affected by road type?

Although only limited literature was found which investigated safety outcomes when a road is classified incorrectly in terms of its function, by looking at studies where road types are compared, it appears that crash/casualty frequency and injury severity risk can all be affected by road type.

1.2.4 How is the effect of road functional class/road type studied?

Road functional class or road type is generally studied as part of a larger study where either other crash characteristics are also being investigated (i.e. multivariate models) or to test the use analysis models in predicting crash outcomes (Jones and Jorgensen, 2003). It is usually examined by analysing real-world collision data and results are usually provided as an Odds Ratio (OR), Coefficients or Relative Risk (RR) using regression models. The five studies considered in this synopsis were from a different country (UK, Italy, Norway, Australia, USA).

1.3 OVERVIEW RESULTS

Overall, the results across four of the five studies showed that the more major road types were found to have a greater risk of crash occurrence and injury severity than the typically more minor roads. However, when only heavy truck-tractors were considered, it was the non-high-speed national roads which appeared to have the greatest risk (Blower et al 1993). Although some studies considered traffic exposure as a factor, it is not clear whether traffic exposure was controlled when investigating road type as a risk factor, so it is possible that this may have had some effects on the outcomes of the studies (e.g. higher traffic levels increase frequency of crash occurrence).

1.4 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound being as they are based on the long established analysis of real world collision data. In keeping with the data source all studies use relatively large sample sizes for investigation. There can be data quality issues especially when considering such large data sets, however all studies appear to apply sound selection methodologies to the data sets. The coded studies mainly investigated crash/casualty frequency (i.e. number of crashes/injured casualties on different road types) and injury severity (i.e. the number of fatal/serious/slight crashes/casualties on different road types).

As only limited literature could be found which analysed safety outcomes regarding having an inappropriately classed road (i.e. the class does not match the actual function of the road) as opposed to an appropriately classed road (i.e. the class does fit the road's function), the search also included studies which involved comparisons of crashes on different road types. In total, 5 relevant studies were identified. Research was carried out across a number of countries in Europe and across the world (UK, Italy, Norway, Australia, USA). Research mainly included crashes involving all vehicle types (4 out of 5 studies), and on one occasion excluded collisions with pedestrians.

2 Scientific overview

2.1 LITERATURE REVIEW

From reviewing the relevant literature, road functional class as a risk factor (i.e. 'wrongly classed road in the wrong place') was found to be a concept that in theory could be analysed using crash data in future studies, but was not actually analysed using data in the studies identified.

For example, in Yannis et al (2013) and Weijermars et al (2008), these studies are mainly concerned with defining road safety performance indicators (SPI) for the road network and design. For the road network, this was done by classifying road categories based on characteristics (e.g. carriageway type, lanes, obstacle free zone, intersections) and then these were linked with the urban centre types that each road 'services'. Then roads across 3 countries were classified based on their current characteristics ('theoretical') and compared with the 'actual' connections (i.e. based on population numbers at the start & end of a connection).

The results showed that, for example, in one test country, 84% of roads which should be 'AAA' class (i.e. motorway) were actually found to be 'AAA' class (so 16% had been wrongly classified). These classifications could be used to compare crash rates for roads which are categorised in the expected road function class against roads which aren't categorised in the expected function class, but is not actually done in these studies. It is an area that is clearly in need of further investigating using real-world data to understand the impact of incorrectly classifying a road for its function in terms of crash risk.

Limited literature specifically investigating the safety effects of 'wrong road in the wrong place' was identified, but a number of studies comparing different road types and crash frequency were found. In these studies, it was found that road type is generally studied as a road characteristic that is used to compare crash frequency when looking at other potential risk factors in crashes. For example, in Blower et al (1993), road type is used to compare crash rates involving tractor trucks with single trailers compared with those with double or no trailers (bobtail) to identify which tractor truck type have the greatest crash risk on which road type.
Often, road type is defined in studies by the road characteristics, which are then often analysed separately. For example, in Jurewicz et al. (2015), the focus is mainly on road geometry issues (e.g. horizontal/vertical alignment, roadside design, intersection types…) on rural roads, and 'crash reduction factors' of specific road design features, but does not consider road type specifically.

Road type can be a complicated topic to analyse using studies from different countries, as classifications of road types can vary across different countries. However in most countries, roads are generally categorised between the national-type roads (e.g. motorway, limited access), regional arterial and local roads, so an approximate comparison can be made between some studies.

2.2 DESCRIPTION OF AVAILABLE STUDIES

Five studies were identified for their inclusion in the synopsis of road type. Four out of the five studies included all vehicle types, with the remaining study focussing specifically on heavy truck-tractors (Blower et al, 1993). One study excluded vehicle collisions with pedestrians (Jones and

Jorgensen, 2003). Table 9 in the supporting document shows the categories of road types used in each of the five studies.

Two studies analysed data at an crash level (Blower et al, 1993 – injury accidents; Stephan and Newstead, 2014 – single vehicle injury accidents) and the remaining three analysed data at a fatal casualty/occupant level (Jones and Jorgensen, 2013 –occupant; Jones et al, 2008 – casualty).

Each study was from a different country (UK, Italy, Norway, Australia, USA) and ranged from studies including national data (e.g. Jones and Jorgensen, 2013) to studies including only data from a local area in that country (e.g. Stephan and Newstead, 2014). All but one study included all crash types and location types in the region where data was collected, while the remaining study focussed on single vehicle crashes in urban areas (Stephan and Newstead, 2014).

Studies investigated the subject of road functional class/road type through observational and cross-sectional studies based on real world collision data. Results were generally provided as an Odds Ratio (OR), Coefficients or Relative Risk (RR) generally through multivariate/multilevel models. Where made, adjustments for associations or variables of interest are through binomial logistic regression analysis. Table 10 in the supporting document illustrates an overview of the main features of the coded studies (sample, method, outcome and results).

2.3 RESULTS

Overall, the results across four of the five studies showed that the more major road types (i.e. those that are typically high speed national roads) were found to have a greater risk of crash occurrence and injury severity than the typically more minor roads (i.e. more typically lower speed local roads). However, when only heavy truck-tractors were considered, it was the non-high-speed national roads which appeared to have the greatest risk (Blower et al 1993).

Using Italian national crash data, Valent et al (2002) found that for all road types outside the urban centre, the risk of all driver/rider types being in a fatal collision was significantly greater, with municipal roads in the urban centre appearing to be the safest. Similar results were also found for risk of death among pedestrians, car drivers, moped and bicycle riders when investigated individually, with municipal road within the urban area again appearing to be the safest.

Stephan and Newstead (2014) found that single vehicle collision frequency in the Melbourne area of Australia was found to be almost double on primary state arterials compared with secondary state arterials, implying that single vehicle collisions are significantly more likely to occur on a primary state arterial road than a secondary state arterial road in urban areas.

Jones et al (2008) also included multilevel negative binomial regression models to identify whether the 'percentage of roads classified as minor' in regions across England and Wales could potentially predict variations in mortality and morbidity. The results implied that in regions with a low percentage of roads classed as minor, the risk of all injury severities was significantly higher.

Jones and Jorgensen (2003) looked at how multilevel models can be used to predict road crash outcome and one of the road characteristics analysed was road type (European grade, National grade, Provincial grade and Local grade). The highest risk of fatal injuries to casualties was found to be on the faster European roads, with the risk also being high on National and Provincial roads, and the lowest risk being on Local grade roads.

The main aim of the study by Blower et al (1993) was to determine whether there were any differences in crash rates involving heavy truck-tractors with one, two or no trailers under various road conditions. Crash rates on various road types ('limited access', 'major', 'other' roads) were investigated and both and 'other' roads and 'major' roads were found to have a significantly greater risk of truck-tractor crashes, compared with 'limited access' roads (7 x risk and 2 x risk respectively). Table 1 presents information on the main outcome of coded studies on road type.

Table 1: Main outcomes of coded studies on road type

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome -description
Blower et al, 1993, USA	Road type	Injury crash count, **Major artery road**	↗	Coefficient estimate= 0.7024, p=<0.05, 95% CI=0.196	Significant increase in risk of injury crashes for heavy tractor trailers compared with **limited access roads**
	Road type	Injury crash count, **'Other' road types**	↗	Coefficient estimate= 1.907, p=<0.05, 95% CI=0.189	Significant increase in risk of injury crashes for heavy tractor trailers compared with **limited access roads**
Jones and Jorgersen, 2003, Norway	Road type	Fatally injured vehicle occupant, **European road**	↗	OR=2.21, p<0.001, 95% CI = 1.69-2.48	Significant increase in risk of fatal injuries for vehicle occupants (including motorcyclists and cyclists) compared with **local grade roads**
	Road type	Fatally injured vehicle occupant, **National road**	↗	OR=1.59, p<0.001, 95% CI = 1.33-1.91	Significant increase in risk of fatal injuries for vehicle occupants (including motorcyclists and cyclists) compared with **local grade roads**.
	Road type	Fatally injured vehicle occupant, **Provincial road**	↗	OR=1.40, p=0.001, 95% CI = 1.15-1.69	Significant increase in risk of fatal injuries for vehicle occupants (including motorcyclists and cyclists) compared with **local grade roads**
Jones et al, 2008, UK	Road type	Fatally Injured casualties, **% of roads classed as minor**	↘	Coefficient estimate = -0.0159, se=0.0031, p<0.001	Significant negative association with the risk of fatally injured casualties compared with **% of roads not classified as minor**
	Road type	Seriously injured casualties, **% of roads classed as minor**	↘	Coefficient estimate = -0.0107, se=0.0033, p<0.001	Significant negative association with the risk of seriously injured casualties compared with **% of roads not classified as minor**
	Road type	Slight injured casualties, **% of roads classed as minor**	↘	Coefficient estimate = -0.0131, se=0.0028, p<0.001	Significant negative association with the risk of slightly injured casualties compared with **% of roads not classified as minor**
Stephan & Newstead, 2014, Australia	Road type	Single vehicle crashes, **Primary state arterial road**	↗	Relative risk = 1.990, 95% CI=1.23-3.23, p=0.005	Significant increase in risk of Single Vehicle Crashes compared with **non-Primary state arterial roads**
Valent et al, 2002, Italy	Road type	Driver/rider involved in a fatal accident, **Provincial road within urban area**	-	OR= 2.92, 95% CI=2.13-4.00	Increase in risk of a driver/rider being involved in a fatal crash compared with **municipal road within an urban area**. Unclear if this result is significant.
	Road type	Driver/rider involved in a fatal accident, **State road within urban area**	-	OR= 2.30, 95% CI=1.76-2.99	Increase in risk of a driver/rider being involved in a fatal crash compared with **municipal road within an urban area**. Unclear if this result is significant.

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome -description
	Road type	Driver/rider involved in a fatal accident, **Municipal road outside urban area**	-	OR= 3.64, 95% CI=2.49-5.31	Increase in risk of a driver/rider being involved in a fatal crash compared with **municipal road within an urban area**. Unclear if this result is significant.
	Road type	Driver/rider involved in a fatal accident, **Provincial road outside urban area**	-	OR= 3.92, 95% CI=3.08-4.99	Increase in risk of a driver/rider being involved in a fatal crash compared with **municipal road within an urban area**. Unclear if this result is significant.
	Road type	Driver/rider involved in a fatal accident, **State road outside urban area**	-	OR= 4.33, 95% CI=3.54-5.28	Increase in risk of a driver/rider being involved in a fatal crash compared with **municipal road within an urban area**. Unclear if this result is significant.
	Road type	Driver/rider involved in a fatal accident, **Highway**	-	OR= 3.81, 95% CI=2.93-4.97	Increase in risk of a driver/rider being involved in a fatal crash compared with **municipal road within an urban area**. Unclear if this result is significant.

↗ = *Significantly greater risk of accident/injury on the road type highlighted in 'outcome variable/outcome type' column compared with the baseline road type (highlighted in 'Main outcome-description column).*
↘ = *Significantly less risk of accident/injury on the road type highlighted in 'outcome variable/outcome type' column compared with the baseline road type (highlighted in 'Main outcome-description column).*
\- = *Differences in crash /injury risk may have been found, but not statistically significant.*

2.4 VOTE COUNT FOR ROAD FUNCTIONAL CLASS/ROAD TYPE

Four of the five papers analysed provided statistically significant results which indicate that certain road types are correlated with more crashes, severe injuries and deaths than others. In the remaining paper, a similar trend is evident however, there is not enough detail in the results to be able to say for definite that they are statistically significant, although the Odds Ratios given indicate that the results are likely to be significant.

Table 2 shows a vote count analysis for the five road type papers. This shows that 60% of the papers (n=3) conclude overall increased accident/injury risk negative effects on road safety whereas no significant outcome or a decrease in accident/injury risk was concluded for 20% (n=1) each.

Table 2: Vote count result of comparing road type studies in terms of crash and injury frequency

Outcome definition	Tested in no. of studies	Result (no. of studies)			Result (% of studies)			Result (no. of effects)			Result (% of effects)		
		↑	-	↓	↑	-	↓	↑	-	↓	↑	-	↓
Crash frequency	2	2	-	-	100%	-	-	3	-	-	100%	-	-
Occupant Injury frequency	3	1	1	1	33%	33%	33%	3	4	5	25%	33%	42%
Total	5	3	1	1	60%	20%	20%	6	4	5	40%	27%	33%

Due to variance between individual reported effects in the papers and differences in the categories of road types used, it was decided the best way to evaluate the topic results would be through a vote count. When analysing the number of effects, the results indicate that only 40% (n=6) of the reported effects led to an increased road accident/injury risk. 27% (4) showed a non-statistically significant result, while 5 effects (33%) showed a decrease in road accident/injury risk.

By displaying the results using the outcome of crash and injury frequencies, it is not possible to see which specific road types are linked to a greater or reduced road accident/injury risk. Therefore, Table 3 shows the vote count results for various road types. Due to the papers included in this synopsis being from five different countries, the categories used for the different road types also differ. So to simplify the results, the road types used in the original studies have been accumulated into three categories shown in Table3.

Table 3: Vote count result of comparing road type studies in terms of road type categories used

Road type definition	**Tested in number of studies**	**Result (number of studies)**			**Result (% of studies)**			**Result (number of effects)**			**Result (% of effects)**		
		↑	-	↓	↑	-	↓	↑	-	↓	↑	-	↓
Major road*	5	3	1	1	60%	20%	20%	5	1	2	62.5%	12.5%	25%
Mid-level road**	3	2	1	-	67%	33%	-	3	4	-	43%	57%	-
Minor road***	5	1	1	3	20%	20%	60%	1	7	7	7%	46.5%	46.5%

Original categories used in the five studies accumulated into the three categories used in the table:
** Major road: 'European', 'Not minor', 'Limited access', 'Primary state', 'Highway'*
*** Mid-level road: 'National', 'Provincial', 'Major artery', 'State'*
**** Minor road: 'Local', 'Minor', 'Other', 'Non-primary state', Municipal'*

The results in Table 3 show that when looking at both number of studies and effects, minor roads more often result in a decrease in road accident/injury risk, whereas major roads more often result in an increase in road accident/injury risk, as do mid-level roads, but not to the same level.

2.5 CONCLUSION

Overall, it was found that minor roads were generally significantly safer than major roads in terms of both crash and casualty frequency and also injury severity. This result was reversed when collisions only involving tractor-trailers were analysed (Blower et al, 1993), which found that 'limited access' (i.e. a high speed freeway) roads were the safest compared with other road types.

This result would generally be expected, as major roads will generally have higher speed limits and speed is a known negative risk factor to road safety in terms of crash frequency and injury risk. Some major roads may also have a greater volume of traffic than minor roads, leading to a greater risk of crash occurring on these road types (i.e. effect of exposure). In addition, longer journeys will be more likely carried out on more major roads, so other risk factors such as fatigue, distraction and road familiarity (i.e. lack of) could also play a part alongside the road type in terms of increasing crash risk on these major road types.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

Literature search was conducted in April 2016. It was carried out in two databases with broadly similar search strategies. The databases 'Scopus' and 'TRID' were browsed through during the literature search. Detailed search terms, as well as their linkage with logical operators and combined queries are shown in Tables 4 and 5.

Table 4: Literature search strategy, database: Scopus

Search no.	Search terms / operators	Hits
#1	"road functional class" OR "road category" OR "road type"	862
#2	"road safety" OR "crash*" OR "accident*" OR "collision*" OR "incident*"	1,001,801
#3	"risk* OR "severity" OR "frequency"	5,838,450
#1 AND #2 AND #3	All years	103

Table 5: Literature search strategy, database: TRID

Search no.	Search terms / operators	Hits
#1	"road functional class" OR "road category" OR "road type"	776
#2	"road safety" OR "crash*" OR "accident*" OR "collision*" OR "incident*"	2328
#3	"risk* OR "severity" OR "frequency"	1203
#1 AND #2 AND #3	All years	28

A number of limitations and exclusions were applied on the 131 papers initially found using the search terms listed in Tables 4 and 5, which were as follows:

- Search field: TITLE-ABS-KEY;
- published: 1990 to current;
- Document Type: ALL;
- Source type: Journals or Conference Proceedings;
- Subject Area: Engineering, Social Sciences ;
- Language: English.

Table 6 shows the number of remaining papers after the limitations and exclusions were applied.

Table 6: Papers still remaining after applying limitations/exclusions

Database	Hits
Scopus	24
TRID	27
Total number of studies to screen title/ abstract	**51**

3.1.2 Results of literature search, screening and prioritizing

As shown in Table 7, the titles and abstracts of the 51 papers remaining after the initial searches and exclusions were screened for their relevance to the risk factor road functional class. From this screening, 11 were found to still have possible relevance to this factor.

Table 7: Screening process of the 51 studies identified from the initial literature search

Total number of studies to screen title/ abstract	**51**
-De-duplication	0
-Not relevant studies excluded	14 from Scopus & 26 from TRID
-Studies with no risk estimates excluded	0
Studies not clearly relevant to the topic (full-text screening later)	0
Remaining studies	11
Studies to obtain full-texts	11

As only 11 studies were found to be of possible relevance, a search for all of the full-texts of these studies was undertaken so that the whole paper could be screened to determine their eligibility for analysing the risk factor road functional class.

Table 8 shows the number of papers which were eligible for analysing road functional class. In addition to the 11 studies identified from the literature search for full-text screening, a further 4 were identified from reference lists in these studies. As the full-text of one study could not be obtained, a total of 14 papers had their full-text screened for eligibility for analysing road functional class. No meta-analyses were found in these 14 studies.

Table 8: Eligibility of papers selected for full-text screening

Total number of studies identified to screen full-text	**11**
Full-text could be obtained	10
Reference list examined Y/N	YES (+4 papers)
Total number of studies which were full-text screened	**14**
Eligible papers	***0***

As can be seen from Table 8, none of the papers selected were found to be relevant for analysing road functional class, so it is clearly not a topic that has been thoroughly investigated in terms of its role as a risk factor in road crash occurrence.

Because no papers of relevance were found, it was decided that the criteria for road functional class should also include studies that looked at road type (i.e. comparing accident/injury frequencies on different road types). Therefore, the fourteen studies included in the full-text screening were screened again for relevance for analysing road type.

Two studies from the above search were found to be relevant enough and have the relevant amount of data to analyse.

A further literature search was undertaken to find further studies relevant to road type and a further three studies were found. These additional three studies were found using a search on Google Scholar using the search term 'road type' AND 'accident' and were among the most relevant available papers containing appropriate analysis results which could be used for analysing road type.

3.2 OVERVIEW OF THE STUDIES IDENTIFIED FOR INCLUSION IN SYNOPSIS

In total, five studies were identified as relevant for this synopsis on road functional class/road type. Table 9 shows the categories of road types used in each of the five studies.

Table 9: Road type categories used in each of the five studies analysed in this synopsis

Author, Year, Country	Road type categories
Blower et al, 1993, USA	• Limited access road* • Major arterial road • 'Other' road type
Jones and Jorgensen, 2003, Norway	• European grade road • National grade road • Provincial grade road • Local grade road*
Jones et al, 2008, UK	• Roads classed as minor • Roads not classed as minor*
Stephan and Newstead, 2014, Australia	• Primary state arterial road • Not a primary state arterial road*
Valent et al, 2002, Italy	• Municipal road within the urban centre* • Provincial road within the urban centre • State road within the urban centre • Municipal road outside the urban centre • Provincial road outside the urban centre • State road outside the urban centre • Highway

** Road type used as a baseline within the study*

Table 10 illustrates an overview of the main features of the coded studies (sample, method, outcome and results).

Table 10: Descriptions of coded studies on road functional class/road type

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Blower et al, 1993, USA	Observational study, log-linear model giving a coefficient estimate (36-cell casualty crash rate model), sample of 6002 Michigan-registered truck-tractors involved in accidents between May 1987 and April 1988 (inclusive).	Regression analysis (coefficient estimate) between injury crash rate and road type (limited access, major artery and 'other' roads)	Limited access road	Analysis results shown for injury accidents only (1352).
Jones and Jorgensen, 2003, Norway	Cross-sectional study, multilevel binary logistic regression model, sample of 16332 KSI casualties between 1985 and 1996 (inclusive)	Regression analysis (Odds Ratios) between fatal injury crashes and non-fatal injury crashes on various road types (European, national, provincial and local grade)	Local grade road	Pedestrians excluded from the study.
Jones et al, 2008, UK	Cross-sectional study, multilevel negative binomial regression model, sample of 1,490,230 injured casualties between 1995 and 2000 (inclusive)	Regression analysis comparing relationship with the number of injured casualties and the percentage of roads classed as minor (compared to non-minor roads)	Roads not classed as minor	
Stephan and Newstead, 2014, Australia	Cross-sectional study, negative binomial regression model, sample of 170 single vehicle collisions between 2005 and 2009 (inclusive)	Regression analysis. Relative risk of single vehicle crash frequency occurrence when a road is/is not a primary state arterial	Not a primary state arterial road	Single vehicle collisions only on urban metropolitan shopping strips divided into road segments at least 200m in length. Signalised intersection crashes excluded.
Valent et al, 2002, Italy	Cross-sectional study, multivariate logistic regression model, sample of 18227 drivers/riders involved in injury accidents between 1991 and 1996 (inclusive)	Regression analysis (Odds Ratios) between risk of fatal and non-fatal injury on various road types (Municipal, Provincial, State, Local Roads (both within and outside urban area) and Highway)	Municipal road within the urban centre	

3.3 LIST OF STUDIES INCLUDED IN SYNOPSIS

Road type papers from initial literature search:

1) Jones, A.P., Haynes, R., Kennedy, V., Harvey, I.M., Jewell, T. and Lea, D. (2008). Geographical Variations in Mortality and Morbidity from Road Traffic Accidents in England and Wales. Health and Place (Volume 14, Issue 3, September 2008, Pages 519-535).

2) Stephan, K. and Newstead, S. (2014). Characteristics of the Road and Surrounding Environment in Metropolitan Shopping Strips: Association with the Frequency and Severity of Single-Vehicle Crashes. Traffic Injury Prevention (15:sup1, S74-S80).

Road type papers from subsequent literature search:

3) Blower, D., Campbell, K. L. and Green, P. E. (1993). Accident rates for heavy truck-tractors in Michigan. Accident Analysis & Prevention (Volume 25, Issue 3, June 1993, Pages 307–321).

4) Jones, A. P. and Jørgensen, S. H. (2003). The use of multilevel models for the prediction of road accident outcomes. Accident Analysis & Prevention (Volume 35, Issue 1, January 2003, Pages 59–69).

5) Valent, F., Schiava, F., Savonitto, C, Gallo, T., Brusaferro, S., Barbone, F. (2002). Risk Factors for fatal road traffic accidents in Udine, Italy. Accident Analysis and Prevention (Volume 34, Issue 1, January 2002, Pages 71–84).

3.4 REFERENCES ON FURTHER BACKGROUND INFORMATION

1) US Department of Transportation, Federal Highway Administration (2013). Highway Functional Classification Concepts, Criteria and Procedures, 2013 Edition. Publication Number: FHWA-PL-13-026.

2) Weijermars, W., Arsénio, E., Cardoso, J., Azevedo, C. L., Chaziris, A., Papadimitriou, E., Yannis, G., Gitelman, V., Duivenvoorden, K., Schermers, G. (2008). Safety Performance indicators for Roads: Pilots in the Netherlands, Greece, Israel and Portugal. Deliverable D3.10c of the EU FP6 project SafetyNet. Contract.

3) Yannis, G., Weijermars, W., Gitelman, V., Vis, M., Chaziris, A., Papadimitriou, E., Azevedo, C. L. (2013). Road safety performance indicators for the interurban road network. Accident Analysis & Prevention (Volume 60, November 2013, Pages 384–395).

Synopsis 7:
Road surface – inadequate friction

1 Summary

Leskovšek, B., September 2016

1.1 COLOUR CODE

Colour code: red.

There is a strong statistical relationship between road surface condition and road safety outcomes. The most significant impact can be attributed to the friction. Improving road surface friction reduces the number of accidents. The effects are greatest on wet roads and when friction initially is low. Friction seems to be more important for accident rates than other road surface deficiencies e.g. unevenness. Studies have also shown that ruts (a sunken track made by the passage of vehicle) have a rather insignificant impact on road safety. On dry roads, ruts improve road safety by slowing traffic speed; however, on wet roads ruts create risk of aquaplaning. Unevenness, in comparison with ruts, has a more significant and negative impact on road safety.

1.2 KEY-WORDS

Road surface, Snow, Ice, Winter road safety, Coefficient of friction, Adhesion coefficient, Friction measurements, Winter road maintenance, Accident rate, Skid resistance, Anti-skid road surface.

1.3 ABSTRACT

Road surface or pavement is the durable surface material laid down on an area, intended to sustain vehicular or foot traffic. Our focus was on primarily surfaced rural roads and not gravel roads. The most commonly used material is asphalt. Skid resistance is one of the most important surface properties with regard to safety, directly related to friction adequacy; it decreases continuously with time, due to the polishing action of the traffic. The road conditions are also distinguished by adhesion coefficient; good adhesion coefficient plays a decisive role in preventing a rear-end collision. Several studies have shown that there is a significant correlation between accident risk due to skidding and the pavement's skid resistance. Improving road surface friction reduces the number of accidents. The effects are greatest on wet roads, in sharp bends and when friction is initially low. Poor pavement conditions at low-speed roads result in less severe crashes for single-vehicle collisions but more severe crashes for multi-vehicle collisions. In the case of single-vehicle collisions at low-speed and multi-vehicle collisions at medium- and high-speed, higher severity levels are observed when pavement conditions are poor.

1.4 BACKGROUND

1.4.1 What is the effect of road surface on road safety?

When roads are dry and free from contaminant materials, the friction between the tyre and the road is usually high. Wet roads have significantly lower levels of friction and skidding/loss-of control can occur. There is a complex interplay of location, traffic level, surface texture and the mechanical properties of the surfacing aggregates, which are required to balance in order to deliver safer roads, and to deliver accident remedial schemes that are effective in the long term.

To provide a surface with appropriate properties it is necessary to understand the interrelationship between a number of fundamental (and measurable) characteristics of the road surface and specify accordingly. The most relevant property with respect to this project is that of skid resistance. The three important characteristics of the road surface that relate to wet road skid resistance under most conditions are: (1) good macro-texture of the surface, which is needed to maintain skidding resistance at higher vehicle speeds and to enable low resilience tyres to improve braking performance; (2) adequate micro-texture of the surface; (3) adequate drainage of water from the road surface.

1.4.2 What is the effect of road surface on accident type?

The skid resistance of a road pavement is an important road safety factor, especially when the road surface is wet. A concentration of accidents on a wet surface can therefore be an indicator of friction deficiency. Several studies have shown that there is a significant correlation between accident risk due to skidding and the pavement's skid resistance. Improving road surface friction reduces the number of accidents. The effects are greatest on wet roads, in sharp bends and when friction is initially low. Friction seems to be more important for accident rates than other road surface deficiencies e.g. unevenness.

Poor pavement conditions at low-speed roads result in less severe crashes for single-vehicle collisions but more severe crashes for multi-vehicle collisions. In the case of single-vehicle collisions at low-speed and multi-vehicle collisions at medium- and high-speed, higher severity levels are observed when pavement conditions are poor. Incorporating safety analysis into the pavement management is one of the urgent needs for more effective and safer management of roadway systems.

1.4.3 How is the effect of road surface studied?

The present overview focusses on recent studies. The most commonly used methods are negative binomial regression and Bayesian logistic regression models. The variation in crash rates over time is explained by various time intervals of execution of experiments and observations (different months of the year), different types of surfaces (asphalt, gravel, grass, sand etc.), different roadway geometries and weather conditions, by different speed limits etc.

For the majority of presented studies, their national accident or other traffic related database were used as a starting point. One study was conducted using a simulator; the majority was conducted in the form of field experiments. One of the studies is dealing with measuring bicycle braking friction on winter road surface conditions, all others are dealing with car drivers.

1.5 MAIN CONCLUSION

16 studies present the effect of different road surface conditions in various countries. Studies are, in the great majority, dealing with inadequate friction. A few of them are dealing with winter conditions (snow and ice on the road), there is one study about calibrating Safety Performance Functions (SPFs) that can predict the frequency per year of injuries and fatalities on homogenous road segments. Here are the main conclusions:

- Pavement surface skid resistance can improve safety of urban intersections (7.5% decrease in accident rate as the friction number increase by 1%).
- Poor pavement condition decreases the severity of single-vehicle collisions on low-speed roads whereas it increases their severity on high-speed roads. On the other hand, the poor pavement condition increases the severity of multiple-vehicle crashes on all roads.
- Low friction is associated with higher crash rates (for both, wet- and dry- conditions).
- Reduction of coefficient of friction (CF) and texture depth (TD) brings an increase in the accident risk.

2 Scientific overview

2.1 LITERATURE REVIEW

Surface texture is the most important feature of the road surface, affecting tyre/road interaction processes such as friction, tyre wear, exterior vehicle noise emission, interior vehicle noise emission, light reflection and rolling resistance.

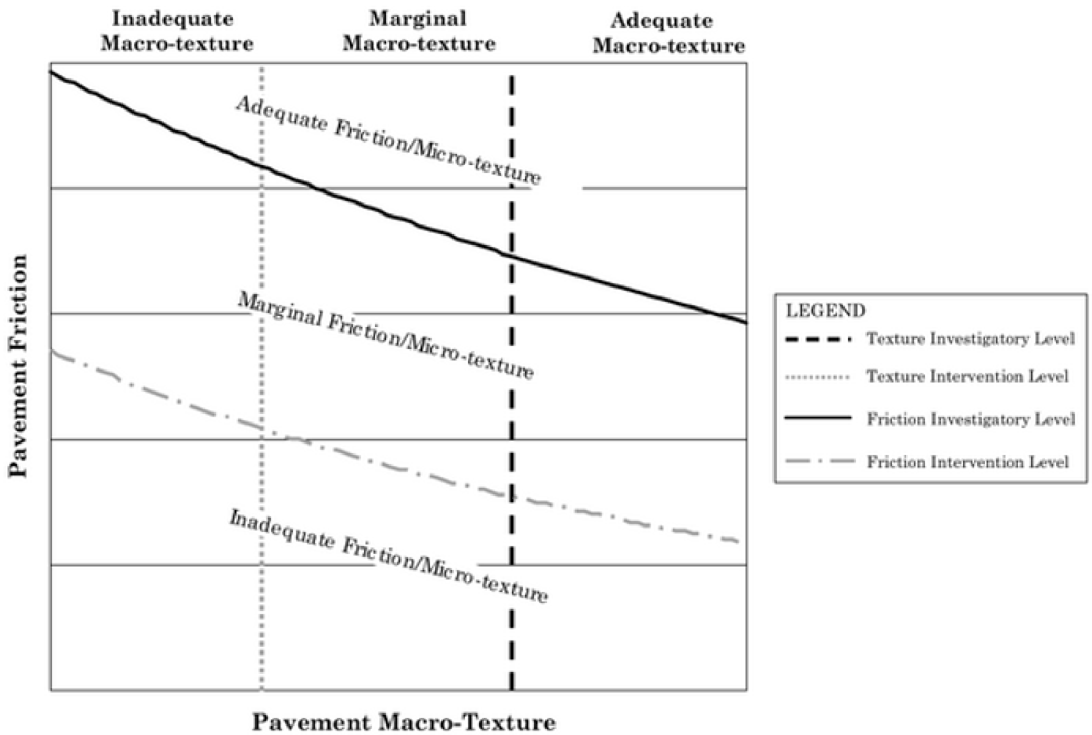


Figure 2.1: Determination of Friction and/or Texture Deficiencies using the IFI (Source: AASHTO, 2008)

One of the main factors influencing traffic safety is the friction between the vehicles' tyres and the road surface. Maintaining a certain safety level demands that driver adapt their behaviour to changing friction conditions, mainly by adjusting their speed (Sandberg, 1998).

2.1.1 What is the effect of road surface friction on road safety?

Road friction is very important for traffic safety. It is defined as the resistance to motion between two surfaces in contact. Its magnitude is expressed by the coefficient of friction (SFC) which is a ratio of two forces, one parallel to the surface of contact between two bodies and opposed to their motion (the friction force) and the other perpendicular to this surface of contact (the normal force). In the context of road transportation, the surface of contact is the road-tyre interface and the normal force is the wheel load. The coefficient of friction ranges from nearly 0 under icy conditions up to above 1.0 under the best surface conditions. Accident risk due to vehicle skidding on pavements with friction coefficient (SFC) less than 0.45, is 20 times higher than on pavement surface with a SFC higher than 0.60. Moreover, if the SFC of a road is less than 0.30, accident risk is 300 times higher (Transport Department, 1994-2). A high number of accidents on a wet surface can therefore be an indicator of friction deficiency.

Inadequate friction is directly related to low skid resistance. . The road pavement's skid resistance is a significant correlate to crash risk due to skidding, i.e. the accident risk is higher when the skid resistance is low, and therefore constitutes a critical road safety factor, especially when the road surface is wet. Assessing the accident rate for different wet, icy or snowy roadway conditions is a very complex task. There are often swift changes and short duration, so the friction may vary to a great extent with time as well as spatially – longitudinally and laterally on the road. The accident rate is to a high degree depending on the adaptation of the driver behaviour.

It is likely that drivers do not recognize sites with friction / skid resistance problems and as such, they do not reduce their speed at those locations, as would be necessary to maintain their risk at a low level. .

The risk of injury accidents is generally increased when road surface is covered by snow or ice. Winter conditions cause high variations of the adhesion coefficient and its variability has a direct influence on kinematic features of the vehicle and safety of the traffic. In case of road accident, determination of the adhesion coefficient for the existing weather and pavement conditions is very crucial for the reconstruction of the accident. The slipping distance of a car is determinated by adhesion coefficient when it brakes and the good adhesion coefficient plays a decisive role in preventing a rear-end collision. In the dry case, the adhesion coefficients of concrete pavement and asphalt road are almost the same, but they show obvious difference after the rain, snow or in ice condition.

There is evidence from several studies to indicate that two main characteristics of pavement surface affect skid resistance: microtexture and macrotexture. The role of each in providing sufficient friction varies depending on the vehicle speed (Noyce et al., 2005). However, the most critical factor affecting skid resistance is pavement macrotexture, which is the feature that increases skid resistance at high travel speed. The in-service micro- and macro- texture properties of the road surface are a function of the physical properties of the aggregates used in the road construction, the design of the surface and the characteristics of both the road layout and the traffic levels using it. It should be clear that this dynamic interplay results in surface characteristics that may significantly vary with the seasons and with changes in traffic levels.

Even under the same conditions, the rate at which individual aggregates polish and/or wear will vary. Moreover, the relationship between these two properties is not consistent and, in order to achieve the appropriate level of in-service skid resistance, the road designer must fully appreciate how his chosen aggregate will perform over time. It is possible to rank resistance to polishing through a test, which applies a standard cycle of roughening / polishing then measures the resulting skid resistance – the Polished Stone Value (PSV) test. The results of testing give road designers a valuable pointer to the likely performance of an aggregate in-service. However, the in-service skid resistance of a road surface is dependent on many factors other than the properties of the aggregate, such as the nature of the surfacing used, the season of the year, the layout of the road and the intensity of traffic using it.

Nowadays the monitoring of pavement skid resistance plays an increasingly important role in evaluating pavement quality, planning pavement rehabilitation and determining rehabilitation alternatives. Urban intersections are among the most accident prone locations. Road surface characteristics, particularly skid resistance of surface, play a major role in the accident rate of intersections.

2.1.2 Other road surface deficiencies

A measure of the regularity of a road surface is called evenness. All types of road surfaces deteriorate at a rate, which varies according to the combined action of several factors (for example: the axial load of vehicles, the traffic volumes, the weather conditions, the quality of materials and the construction techniques). These deteriorations have an impact on the road surface roughness by causing cracking, deformation or disintegration. Water concentration on these deteriorations increases the risk of vehicles skidding.

When the evenness of a whole road section has sharply deteriorated, users tend to reduce their speed in order to maintain their comfort at an acceptable level, thus minimizing potential safety impacts. Pavement roughness can be more detrimental to safety when problems are localized, unexpected and significant. Such situations can generate dangerous avoidance manoeuvres, losses of control or mechanical breakdowns of vehicles, thereby increasing the risk of accidents. Reductions in skid resistance caused by vertical oscillations of vehicles on uneven road surfaces can prove problematic, especially for heavy vehicles and when the problems are isolated. However, an improvement in the evenness quality associated with resurfacing might result in speed increases. That means that it has a slightly negative safety effect.

2.2 CRASH DATA SCENARIOS

This crash scenario analysis was conducted using cases from the German In-Depth Accident Study (GIDAS) database collected in the years 2007 to 2015. In total, records from 14.398 accidents, which occurred in the regions of Hannover and Dresden, were analysed. The GIDAS database details those accidents, which occurred on a public road where at least one person was injured. The accidents are collected according to a statistical sampling process to ensure a high level of representativeness of the actual accident situation in the sample regions. The data collection is conducted using the "on the scene" approach where all factors, which were present at a crash, are recorded. This does not mean that the recorded factor was a contributory factor towards the crash. For the current analysis all crashes where road surface was listed as present at the crash scene were compared to all crashes road surface was not present at the crash scene. Note that, the risk factor is identified in relation to the involved party who was considered most at fault.

The data suggest that, while accidents at junctions have a slightly higher share among crash types in dry road surface conditions, there is a clear over-representation of accidents at junctions in wet road surface conditions, together with a slight increase of single-vehicle on-road crashes. Moreover, in ice or snow road surface conditions, single vehicle crashes (on-road and run-off road) are increased.

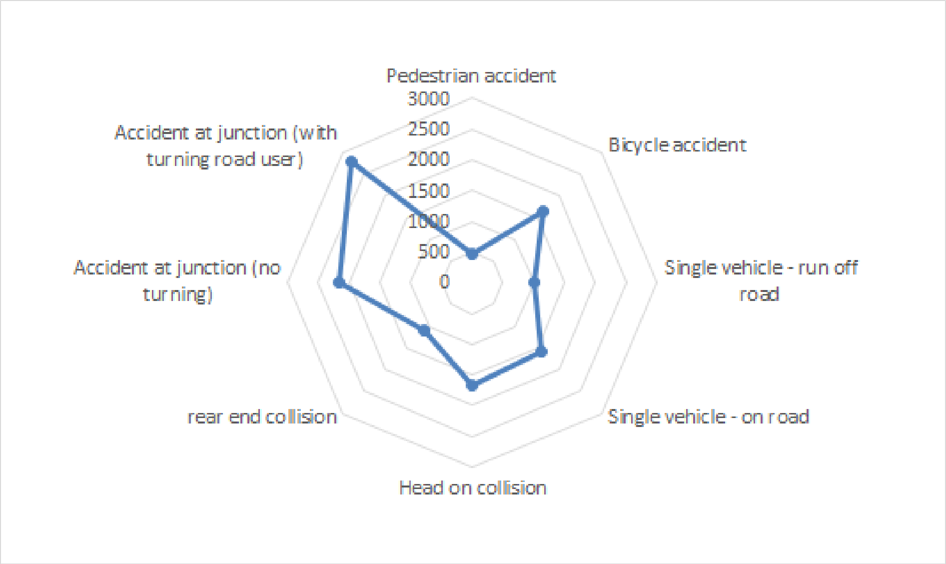


Figure 2.2: Accident types in dry road surface (source: Gidas)

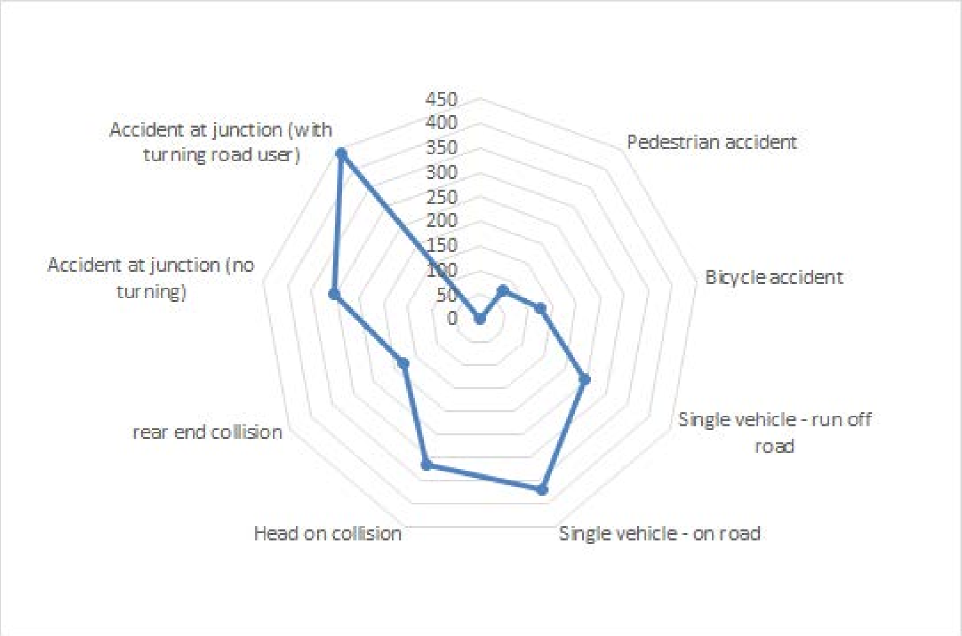


Figure 2.3: Accident types in wet road surface (source: Gidas)

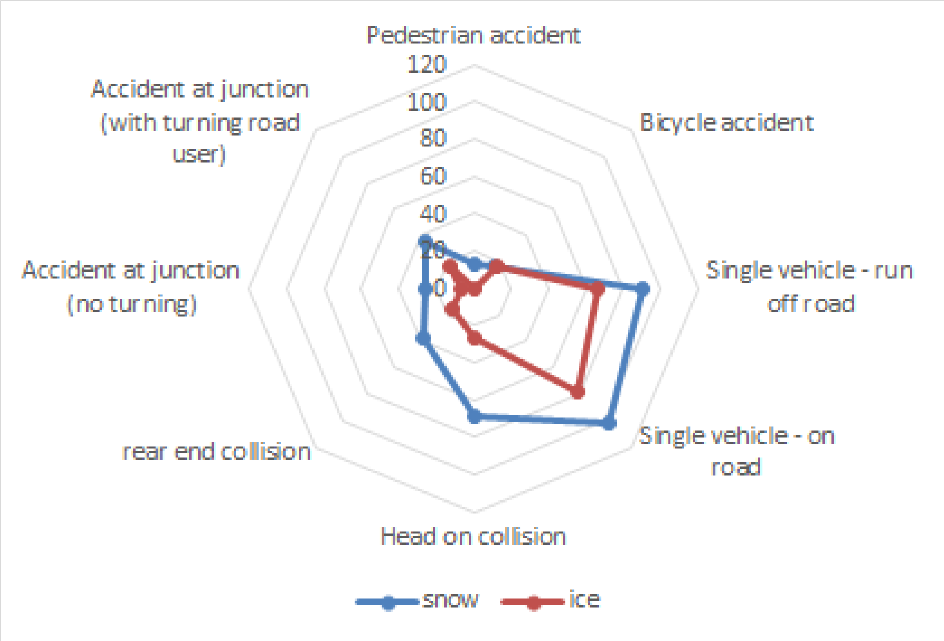


Figure 2.4: Accident types in snow or ice (source: Gidas)

2.3 DESCRIPTION OF STUDIES

16 studies researching the risk and the effect of road surface have been coded, analysed and summarized. The most commonly used methods in the presented studies were negative binomial regression and Bayesian logistic regression model. In addition to these two methods in other studies we were also dealing with different regression analysis, with extended Prospect Theory based acceleration model, with a single level generalized negative binomial model and multilevel Poisson lognormal model, , with different parametric and non-parametric methods, etc.

Coded studies on road surface are dealing with these main objectives:

- statistical analysis on the data from national database to investigate the possible correlations between skid resistance indicator and influential factors for Hot Mix Asphalt surfaced pavements;
- relating the crash data to the AADT, skid resistance and horizontal radius of curvature by using negative binomial regression
- exploring the effect of the road features of two-lane rural road networks on crash severity;
- identifying the relationship between rate of accidents at intersections and the road surface skid resistance based on experimental approach;
- establishment of threshold values based on safety criteria and concerning skid resistance and macro texture, represented by International Friction Index, coefficient of friction and texture depth;
- evaluation of effect of friction on both wet- and dry-condition crashes by using regression analysis;
- measuring actual braking friction of bicycles in winter conditions and comparing the results to friction measurement devices;

- identifying the factors affecting winter road safety and quantifying the effect of winter road maintenance on road collisions during snow storm events by using disaggregate modelling approach.

2.4 DESCRIPTION OF ANALYSIS CARRIED OUT

The following table (table 2) present the main outcomes from the coded studies. The effects on road safety are coded as

↗ = significant increase of crash/victim numbers or of crash risk = threat to road safety
↘ = significant decrease of crash/victim numbers or of crash risk = improvement of road safety
- = no significant change

Table 2.1: Summary of study results

Author, Year, Country	**Exposure variable**	**Outcome variable**	**Effects for Road Safety**	**Main outcome - description**
Buddhavarapu, Smit, Prozzi; 2015, United States	PFC overlaid road segments vs. non-PFC road segments	Safety effectiveness as the change in the expected crash count from pre- to post-installation period.	- Crash modification factor = 1.0280	The hypothesis that PFC is effective in reducing wet weather crashes has not been accepted. Safety effectiveness of PFC road surfaces largely relies on its interrelationship with the road user. The safety infrastructure must be cautiously used to reap the benefits of the substantial investments. PFC is providing improved levels of service under severe rain events by allowing road users to drive at the posted speed limits.
Najafi, Flintsch, Medina; 2015, United States	Pavement friction (wet and dry condition)	Crash rate	↘ The slope of the regression line is negative for all cases except for Urban Freeway Expressway dry-condition crashes.	Friction was found to be a significant factor affecting the ratios of both wet- and dry-condition car crashes. Factors such as seasonal variation and temperature changes can also affect the friction measurement.
McCarthy, Flintsch, Katicha, McGhee, Medina-Flintsch; 2016, United States	Grip Number (GN) effect	Extended scope of current SPF models and proposal of a method of prioritizing road segments.	↘ Road's slopes: Interstate=-1.19 Primary=-1.00 Secondary=-0.56	The average crash risk is expected to increase with decreases in GN. Therefore, it's possible to reduce the average crash risk by applying a treatment for skid resistance (increasing GN). Using the methodology provided, locations could be prioritized based on the difference in empirical Bayes Method crash risk before a GN treatment and the GN after treatment.
Lee, Nam, Abdel-Aty; 2015, United States	Poor pavement condition	Crash severity level	- Multi-vehicle crashes under poor pavement condition are more likely to cause higher injury-severity levels.	The Bayesian ordered logistic regression models indicated that the poor pavement condition decreases the severity of single-vehicle collisions on low-speed roads but it increases their severity on high-speed roads.
Bystrov, Abbas, Hoare, Tran, Clarke, Gashinova, Cherniakov ;	Road Surface Recognition Classification Algorithms	The most effective model for differentiation between	-	The most effective proved to be multilayer perceptron (MLP) method based on the use of neutral network. The average probability of correct recognition in this case was 99%. This method can be used for the initial rough

2015, United Kingdom		asphalt, gravel, grass and sand		classification between significantly different surfaces. The study is a test of how well measurement technology can classify different types of road surfaces. That is useful for rapid collection of data about road surfaces.
Rekila, Klein-Paste ; 2015, Norway	1) actual braking friction of bicycles in winter conditions; 2) measured friction from devices (FMDs)	Differences between 2 methods: deceleration and braking distance	↑ Friction=0.41	Both methods are suitable for defining bicycle friction. The deceleration was found to be a more accurate method in the given field conditions. The bicycles experienced the same or higher friction than the FMDs. Bicycling is becoming a more and more common mode of transportation in European cities. Winter conditions create a challenge for providing a high quality, functional bicycle network. If we want to set standards for winter maintenance of cycleways, this also includes a friction criterion.
Elvik; 2016, Norway, Denmark, United States, Sweden	Time between 2 studies (20 years).	Accidents.	-	Many road traffic safety measures are intended to influence a specific risk factor. Winter road maintenance in intended to clear roads from snow. It certainly becomes less effective if the risk associated with snow is not as great as before. It is also reasonable to think that improvements in weather forecast, de-icing methods and other elements of winter road maintenance has made it more effective.
Wei, Yanfang, Xingli; 2011, China	Anti-skid road surface (m), Asphalt pavement (m), Wet pavement (m), Snow road (m), Ice road (m).	Design values of minimum safety distance under different road conditions.	↑	The velocities of cars on the highway are usually very high. In order to prevent traffic accidents effectively, the driver should control the speed well and make sure of a safe distance. The minimum safe distances gradually increase with the decreasing friction coefficient. That indicates the smoother the road, the greater the minimum safety distance.
Usman, Fu, Miranda-Moreno; 2012, Canada	Surface conditions.	Road collision occurrence.	↑	Factors such as visibility, precipitation intensity, air temperature, wind speed, exposure, indicator for month, trend within storm and site-specific factors have statistically significant effects on winter road safety. Road surface conditions were found to have a signification contribution to the variation of collisions within and between individual storms and maintenance routes.
Fernandes, Neves; 2013, Portugal	Pavement surface properties.	Expected number of accidents.	↑	The analysis has shown that there was an increase in the accident risk with the reduction of coefficient of friction and texture depth in all road environments.
Russo, Busiello, Dell'Acqua; 2016, Italy	Road segments reflecting base geometric conditions.	Safety Performance Functions.	↑	The factors having greatest impact on the yearly frequency of crash injuries and fatalities to be predicted were recognised as Segment Lenght (L), Annual Average Daily Traffic (AADT), Lane Width (LW), Horizontal Curvature Indicator (CI) and Vertical Grade (VG).
Amini, Beigi; 2014, Iran	Pavement surface skid resistance.	Rate of accidents at intersections.	↓ Slope = -7.466 95%	The relationship between accident rate and the independent variables including skid resistance and speed was modelled using a loglinear regression. The model results were significant at 95% confidence level. The model results showed that the friction had a relatively significant effect on the accident rate. In addition, the model analysis showed that assuming a usual speed for the major and minor roads (20 km/h to 40 km/h),

				the accident rate would decrease by 7,5% as the friction number increases by 1%.
Song, Chen, Smith, Hedfi; 2005, United States	Surface age, traffic intensity, average daily temperature, average daily rainfall.	Skid resistance	↓	The skid resistance of Hot Mixture Asphalt pavements is affected by the pavement locations due to the different traffic fashions. The friction number on rural roads is higher than that on urban roads by 6-7 units on the average. The friction number on roadways seems to reaches a steady state condition in about one year after resurfacing. The correlation between friction and traffic intensity on urban roads is very weak. On rural roads, the friction decreases linearly with the natural logarithms of Annual Average Daily Traffic per lane. The result of the study shows difference of friction between urban roads and rural roads which reveals that traffic fashion (speed, stopping frequency and etc.) would play a more important role than traffic intensity in the polishing of surface.
Hamdar, Qin, Talebpour ; 2016, United States	Different roadway geometries and weather conditions.	Reflection of change in risk-perception and acceleration maneuvering.	↑	Drivers invest more attention and effort to deal with the roadway challenges compared to the effort to deal with the weather conditions.
Walus; 2016, Poland	Fresh snow covered road surface, ambient temperature.	Acceleration, Mean Fully Developed Deceleration	↑	4 series of experimental research were done in different temperature conditions for the road surface covered with fresh snow. The lowest values of acceleration during speeding up were presented on January 25 2013. During that day the ambient temperature and temperature of fresh snow were the lowest. This fact has caused a surface freezing of snow and it could have formed the "surface snow shell" and could have generated a higher rolling resistance.

In summary, poor road surface increases crash risk due to in adequate friction and uneven surfaces. However, in some studies poor road surface may reduce crash risk, particularly for uneven surfaces which may reduce travel speeds.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature search strategy

A literature search was conduced in March 2016. It was carried out in 3 databases (Scopus, ScienceDirect and Web of Science) using the same strategy. Details of search terms used are listed in the following tables. Search results were limited to journal papers and conference proceedings in English language, published after 1999. Other already known or during the literature search occasionally (e.g. via Google) found studies as well as studies found in the literature search for other topics and including road surface were added on the list for studies to be coded.

Database: Scopus **Date:** 30th of March 2016

search no.	search terms / operators / combined queries	hits
#1	(„road surface“)	3.176
#2	("road casualties" OR "road fatalities" OR "traffic accident" OR "road crash" OR "collision")	23.493
#3	("road safety" OR "traffic safety")	3.261
#4	#2 within #1	208
#5	#3 within #1	256
#6	#3 within #4	100
#7 (within #6)	("inadequate friction" OR "uneven surface" OR "ice" OR "snow" OR "oil" OR "leaves")	**21**

(Optional but recommended: Limitations/ Exclusions:
Search field: TITLE-ABS-KEY
Published: 1999 to current
Document Type: "Article" and "Conference paper"
Language: "English"
Source Type: „Journals“ and "Conference Proceedings"
Exclusion of several countries
Subject Area: „Engineering“)

Database: Scopus **Date:** 29th of March 2016

search no.	search terms / operators / combined queries	hits
#1	(„road surface“)	3.176
#2 (within #1)	("road casualties" OR "road fatalities" OR "traffic accident" OR "road crash" OR "collision")	208
#3 (within #2)	("inadequate friction" OR "uneven surface" OR "ice" OR "snow" OR "oil" OR "leaves")	38
#4 (within #3)	("road safety" OR "traffic safety")	**21**

Database: ScienceDirect **Date:** 30th of March 2016

search no.	search terms / operators / combined queries	hits
#1	(„road surface“)	382.058

#2	+ some *Limitations/ Exclusions*	2.387
#3	AND ("road safety")	**2**

Database: Web of Science **Date:** 30th of March 2016

search no.	search terms / operators / combined queries	hits
#1	(„road surface")	15.159
#2	AND ("road safety" OR "road fatalities" OR "road crash")	84
#3	+ + some *Limitations/ Exclusions*	**2**

Results Literature Search

Database	Hits
Scopus (remaining papers after several limitations/exclusions)	21
ScienceDirect	2
Web of Science	2
Total number of studies to screen title/ abstract	**25**

Eligibility

Total number of studies to screen full-text	25
Full-text could be obtained	25
Reference list examined Y/N	partly
Eligible papers	**25**

Screening of full texts

Total number of studies to screen title	25 + google
-De-duplication	5
-not relevant studies excluded	5
-studies concerning measures excluded	5
-studies with no risk estimates excluded	3
-studies excluded due to limited time ressources	6
Remaining studies	15
Number of studies dealing with "inadequate friction"	7
Number of studies dealing with "snow & ice"	4
Number of studies dealing with "uneven surface"	2
Number of studies providing additional information to understand the road surface topic	2

Prioritizing Coding

- Prioritizing Step A: meta-analysis first
- Prioritizing Step B: studies, published more recently
- Prioritizing Step C: studies from Europe

No meta-analyses were found. In selecting studies for coding, we gave a priority to studies, published more recently. We also gave a priority to studies from Europe over studies from the rest of the world.

3.1.2 Analysis of study design and methods

Environmental conditions have been identified to have major impact on driver behavior. Examples of different environmental conditions are weather-related and roadway geometry-related factors. Moreover, weather condition and road geometry are the two congestion and crash triggering factors. Studies point to the strong relationship between road safety and congestion, with the highest accident rates happening in the peak traffic period. The friction coefficient of the road surface, which influences vehicle's maneuverability, has been widely studied.

3.1.2.1 Inadequate friction

Skid resistance indicates the contribution of the road surface to the generation of friction between the tyre and the road surface. It is one of the most important surface properties with regard to safety. Moreover, it is one of the factors that determine braking distance and sliding forces in a sharp bend. The skid resistance of an asphalt surfacing decreases continuously with time, due to the polishing action of the traffic.

As a tire travels over a pavement surface, its interaction with the pavement results in forces called tire-pavement friction that resists the relative direction of motion of the tire. Tire-pavement friction or skid resistance is expressed as a dimensionless quantity called the coefficient of friction, which is computed by dividing the vertical force by the longitudinal force.

Surface friction is generally given by the equation $F = f \times W$, where:
F = tractive force (horizontal force applied to the test tire at the tire-road surface contact);
f = friction factor or friction coefficient:
W = Vertical load applied to the tire.
The value of the friction coefficient depends upon several factors including tire pressure, tire wear and inflation pressure, vehicle speed; environmental conditions (wet and dry), road surface temperature, aggregate angularity and asphalt content (Amini et al., 2014).

Studies showed that friction was found to be a significant factor affecting the ratios of both wet- and dry-condition car crashes.

Buddhavarapu et al. (2015) conducted a fully Bayesian before-after analysis of permeable friction course (PFC) pavement wet weather safety. PFC is a porous hot-mix asphalt. In this study, two groups of road segments overlaid with PFC and non-PFC material were identified across Texas. A negative binomial data generating process was assumed to model the underlying distribution of crash counts of PFC and reference road segments to perform Bayesian inference on the safety effectiveness. Also controlled in the model specification were traffic volume, length of the project, climatic condition, facility type, etc. The hypothesis that PFC is effective in reducing wet weather crashes has not been accepted. Therefore, the findings of this study are in agreement with European literature on the safety benefits of porous surfaces (Elvik et al., 2005, Zwan, 2011) . The study suggests that the safety effectiveness of PFC road surfaces, or any other safety infrastructure, largely relies on its interrelationship with the road user. The safety infrastructure must be cautiously used to reap the benefits of the substantial investments. However, there is no doubt that PFC is providing improved levels of service under severe rain events by allowing road users to drive at the posted speed limits. In addition, the environmental benefits of PFC including noise reduction and improved run-off water quality encourage the continued use of OFC surfaces.

Najafi et al. (2015) evaluated the effect of friction on both wet- and dry- condition crashes. Several studies have suggested that reduced friction during wet weather conditions, due to water on the pavement surface reducing the contact area between the tire and the pavement, increases vehicle crashes. The New Jersey Department of Transportation provided data for the study. Regression analysis was performed to verify the effect of friction on the rate of wet- and dry- condition car crashes for various types of urban roads. Friction was found to be a significant factor affecting the ratios of both wet- and dry- condition car crashes on urban roads. It is also suggested that the relationship is not linear but a logarithmic transformation was necessary. Factors such as seasonal variation and temperature changes can also affect the friction measurement. This effect needs to be further investigated and incorporated into the pavement friction management program.

McCarthy et al. (2016) extended the scope of current Safety performance Function (SPF) models to also consider the effect of Grip Number (GN) and curvature (CV). The study also proposes a method of prioritizing road segments according the benefit received from applying a GN treatment. The crashes were evaluated as a function of Annual Average Daily Traffic (AADT), GN and CV by using Poisson-gamma regression. For this paper, a crash study was carried out for the interstate, primary and secondary routes in the Salem District of Virginia. The data used in the study included information on 2010 to 2012 crash data, 2010 to 2012 AADT and horizontal radius of curvature. Additionally, skid resistance was measured using a continuous friction measurement, fixed-slip device called a Grip Tester. Negative binomial regression was used to relate the crash data to the AADT, skid resistance and CV.

For each route type (interstate, primary and secondary), the statistical analysis showed GN to be statistically significant to the SPF models. An interpretation of this result suggests that, regardless of route type, when assessing the crash risk of any road segment the accuracy of the model prediction can be improved by adding GN as a variable. When using SPF model, the empirical Bayes method (EB) can be used to estimate a close approximation of a network's "true" crash risk. It can also be used for individual segments. Therefore, the EB estimate can be used for preliminary screening of networks for road segments with high crash risk for further investigation.

Rekila et al. (2016) deal with measuring bicycle-braking friction in winter conditions in Norway. The study has two main objectives: 1) to measure actual braking friction of bicycles in winter conditions and 2) to compare the results of friction measurement devices (FMDs). Two methods were used to measure bicycle friction in the study – deceleration and braking distance. Both methods were found to be suitable for measuring bicycle friction and are convenient and inexpensive to use. Two instrumented bicycles with studded winter tires were tested by all-out braking tests on winter road surfaces. As a comparison, friction of the test stretch was measured by three FMDs. Despite the variation in friction measurements through different instruments, it is sensible to set a friction standard for cycleways to ensure proper maintenance during winter conditions for all users.

During the study, the general question was often posed: "Should we have a friction criterion at all in the standard for cycleways?". Some cyclists pointed out that when biking with studded winter tires, slippery conditions are not a real problem. They seem to prefer a hard and even surface instead of a certain friction. The presence of loose snow on top of cycleways appeared to hamper winter cycling more than simply a "slippery surface". However, cycleways are also being used by other users, such as a mother with pram, a wheelchair user or an elderly person with walker. By removing friction criterion, there would not be real criterion to initiate antiskid treatment such as gritting. Some sort of friction criterion seems therefore sensible but there is a large variation between different FMDs and bicycles. A better definition of an acceptable friction criterion on cycleways is therefore desirable.

Fernandes et al. (2014) deal with threshold values of pavement surface properties for maintenance purposes based on accidents modelling. The main objective of the paper was to present a methodology for the establishment of threshold values based on safety criteria and concerning skid resistance and macrotexture, represented by International Friction Index, coefficient of friction and texture depth. The methodology consists, first, of evaluating of the influence of the pavement surface properties on road accidents and, second, establishing the threshold values for pavement surface properties. The influence of pavement surface properties on accident occurrence was based on the definition of compound road environment (RE), a more appropriate technique for accident modelling. The analysis of the accident risk as a function of pavement surface properties was carried out by setting admissible accident risk levels to establish threshold values for these properties in each RE. From the study of the influence of pavement surface properties on road accidents, three RE were described and chosen to evaluate and establish skid resistance and macrotexture threshold values:

- E1: rural environment with a heavy presence of urban characteristics;
- E2: environment characterised by a considerable predominance of intersections in a rural environment;
- E3: environment with curved segments, high longitudinal gradients and average speed higher than the tolerable speed.

The analysis has shown that there was an increase in the accident risk with the reduction of coefficient of friction and texture depth in all RE.

In E1, the safety in curve was very problematic in case of high speeds due to small radius curves. Regarding the safety in emergency braking, higher friction coefficient values were needed for the reduction of the braking distance. Imminent risk of accident in simulated scenarios has corresponded to minimum values of skid resistance between 40 and 50.

In E2, the main safety concern was the braking distance in curved or straight alignments. High skid resistance was needed for emergency braking. In curves with large radius of curvature, low skid resistance levels leaded to small trajectory deviations without the vehicle losing control. In the case of small curvature radii, low skid resistance levels originated in the vehicle overturn. The simulations showed that the risk of accident increases for values of skid resistance between 40 and 60.

In E3, the main problematic scenarios were driving in curve and braking in straight alignments with low skid resistance. In the case of curves with small curvature radii, higher skid resistance was fundamental to ensure a safety driving at high speeds.

Urban intersections are among the most accident prone locations. Road surface characteristics, particulary skid resistance of surface, play a major role in the accident rate of intersections. Amini and Beigi (2015) study aims to identify the relationship between rate of accidents at intersections and the road surface skid resistance based on an experimental approach. For this purpose, 32 un-signalized intersections in Teheran were selected. The intersections data including accident, traffic and friction coefficient data were collected. Nearly 200 crashes occurring at these intersections in wet conditions were analysed. To determine the skid resistance, a new device was made and calibrated to obtain the International Friction Index. The relationship between accident rate and the independent variables including skid resistance and speed was modelled using a loglinear regression. The model results were significant at 95% confidence level. The model results showed that the friction had a relatively significant effect on the accident rate. In addition, the model analysis showed that assuming a usual speed for the major and minor roads (20 km/h to 40 km/h), the accident rate would decrease by 7.5% as the friction number increases by 1%.

Song et al. (2005) study investigates the possible correlations between frictional resistance (friction number) and influential factors of Hot Mixture Asphalt surfaced pavements in the Maryland State Highway Administration pavement network. The influential factors include pavement surface age, pavement location (urban or rural), traffic intensity, aggregate properties, slurry seal treatments and climate-related factors. The study showed that the skid resistance of Hot Mixture Asphalt pavements is affected by the pavement locations due to the different traffic fashions (speed and stopping frequency, etc.). The friction number on rural roads is higher than that on urban roads by 6-7 units on the average. The friction number on roadways seems to reaches a steady state condition in about one year after resurfacing. At the steady state condition, the skid resistance deteriorates with ages at a relatively low rate: 0.22 friction number per year on rural roads and 0.26 on urban roads. Urban roads seems to experience a considerable amount of polishing in the first year after resurfacing. The

correlation between friction and traffic intensity on urban roads is very weak. On rural roads, the friction decreases linearly with the natural logarithms of Annual Average Daily Traffic per lane.
Application of aggregates with high Polish Value can improve skid resistance by 3 friction numbers on the average.
It may seem that the relevance of the study for the chosen topic is minor but the result of the study shows difference of friction between urban roads and rural roads, which reveals that traffic fashion (speed, stopping frequency and etc.) would play a more important role than traffic intensity in the polishing of surface.

3.1.2.2 Ice and snow

Multiple studies have focused on the statistical relationships between different traffic measures and different surrounding weather conditions. The overall findings of these macro level studies denote that visibility impairment, precipitation, and temperature extremes may affect driver behaviour and vehicle maneuverability.

Winter conditions represent another factor having a significant impact on the safety and mobility of road users. Winter weather related conditions are costly to the society. To reduce negative impacts, transportation agencies spend significant resources every year to keep roads clear of snow and ice for safe and efficient travel. Even a small increase in slipperiness of section of road can increase the accident rate of the section of road tenfold.

Usman et al. (2012) presented a disaggregated modelling approach for investigating the link between winter road collision occurrence, weather, road surface conditions, traffic exposure, temporal trends and site-specific effects. The study aimed at identifying the factors affecting winter road safety and quantifying the effect of winter road maintenance on road collision during snowstorm events. Detailed hourly data on collision counts along with the corresponding road weather and surface conditions and traffic on 31 patrol routes across Ontario, Canada, over six winter seasons (2000 – 2006) were obtained and used for model calibration.
Two modelling methods were used – a multilevel Poisson lognormal model accounting for within storm correlation and site-specific effects and a single level generalized negative binomial model. Four different models were calibrated and it was found that the within storm correlation is relative weak and generalized negative binomial model has a better fit to the data by virtue of its ability to account for the heterogeneity in the data through varying dispersion parameter. Factors such as visibility, precipitation intensity, air temperature, wind speed, exposure, indicator for month, trend within storm and site-specific factors have statistically significant effects on winter road safety. Road surface conditions were found to have a signification contribution to the variation of collisions within and between individual storms and maintenance routes.

Wei et al. (2011) introduced to analyse how the driver apperceives the state of the front vehicle through the change of the headway. The quantitative relationship between car-following distance and road roughness, velocity, reaction time etc. were induced. Authors have explored the theoretical value of safe distance under different road conditions, such as roads with anti-skid surface, asphalts pavement, rain, snow and ice.
The speeds of cars on the highway are usually very high. In order to prevent traffic accidents effectively, the driver should control the speed well and make sure of a safe distance. It should be noted that the road conditions are distinguished by adhesion coefficient. The slipping distance of a car is determinated by adhesion coefficient when it brakes and the good adhesion coefficient plays a decisive role in preventing a rear-end collision. In the dry case, the adhesion coefficients of concrete pavement and asphalt road are almost the same, but they show obvious difference after the rain. The peak value of adhesion coefficients of asphalt or concrete pavement on dry condition is 0.8. The value decreases to 0.55 on rainy road, and to 0.2 on snow road. Even lower on icy road, only 0.1. The

minimum safe distances gradually increase with the decreasing friction coefficient. That indicates the smoother the road, the greater the minimum safety distance.

Walus (2016) deals with the acceleration and deceleration of a car equipped with winter tyres for the snow-covered road. From November until April, different weather conditions occur which cause high variations of the adhesion coefficient. Their variability has a direct influence on kinematic features of the vehicle and safety of traffic. The antislip features are changing very often for the road surface covered with fresh snow. For this study, four series of experimental research were done in different temperature conditions for the road surface covered with fresh snow that was not compacted by any other vehicles. The measurements of the environment features were done before and after 10 trials of the test. The lowest values of acceleration during speeding up were presented on day when the ambient temperature and temperature of fresh snow were the lowest. This fact has caused a surface freezing of snow and it could have formed the "surface snow shell" and could have generated a higher rolling resistance. Obtaining information on the effect of the environment and road surface parametres is the activity, which allows assessing the safety range of road traffic.

Elvik's paper (2016) reports an exploratory analysis of the stability over time of the association between risk factors and accident occurrence. His paper presents examples of studies that have replicated estimates of risk. All studies were carried out within a given country (different studies from Norway, Sweden, Denmark and USA), using the same method, to ensure that estimates of risk are comparable. One of the risk factors included in the paper is also road surface conditions. The predominant tendency in the studies reviewed in this paper, is that the associations between the risk factors and accidents have become weaker over time. However, this is not entirely consistent. It is likely that innovations in car safety systems may have contributed to the fact that the most recent estimate indicates a smaller increase in risk. Many road traffic safety measures are intended to influence a specific risk factor. Winter road maintenance in intended to clear roads from snow. It certainly becomes less effective if the risk associated with snow is not as great as before. It is also reasonable to consider that improvements in weather forecast, de-icing methods and other elements of winter road maintenance has made it more effective. That could be one of the reasons why the risk associated with snowfall has declined.
The results in the paper, linked to the topic "road surface conditions", are as follows:

- the increase in risk associated with driving on a wet road surface during winter in Sweden has not declined over time;
- the increase in risk associated with driving on a snow- or ice-covered road surface during winter in Sweden has become slightly smaller over time and the regional differences in risk have become substantially smaller;
- the increase in risk associated with rain and snow has become smaller over time in Norway;
- the protective effect of snow depth has become smaller over time in Sweden and Norway.

3.1.2.3 Uneven surface

Many studies have found that pavement conditions significantly influence traffic safety. Lee et al. (2015) focus on the development of the relationship between poor pavement conditions and crash severity levels using a series of Bayesian ordered logistic models for low/medium/high speed roads and single/multiple collision cases. The Bayesian ordered logistic regression models indicated that the poor pavement condition decreases the severity of single-vehicle collisions on low-speed roads, whereas it increases their severity on high-speed roads. On the other hand, the poor pavement condition increases the severity of multiple-vehicle crashes on all roads. The results of this study suggest that the severity levels of most of crash types can be reduced when the pavement condition is well-maintained.

Russo et al. (2016) explored the effect of the road features of two-lane rural road networks on crash severity. The main objective of the paper is to make a contribution for bridging the gap existing in the literature where more road crash frequency prediction models exist than specific functions focused on the prediction of road crash casualties. A 5-year period was selected to carefully analyse the crash reports. A negative binomial regression model was used.
The factors having greatest impact on the yearly frequency of crash injuries and fatalities to be predicted were recognised as Segment Length (L), Annual Average Daily Traffic (AADT), Lane Width (LW), Horizontal Curvature Indicator (CI) and Vertical Grade (VG).
The paper confirms the effectiveness of the Highway Safety Manual (HSM) procedure[1] on the one hand, but on the other hand, it sheds light on the methodology for predicting road crash casualties, suggested by HSM for rural undivided roads but which overestimates the observed crash frequency.
The effect of geometric variations by changing the values of the variables numerically makes it possible to quantify the benefit for the studied network in terms of a reduction in the yearly frequency of injuries and fatalities and all casualties, depending on whether the investigated road segment comes under base (where vertical grade is less or equal 1% and horizontal curvature is more or equal 0.8) or non-base geometric basic conditions.

3.1.2.4 Road surface tests

The development of remote surface recognition systems is an important step in ensuring road safety. Bystrov et al. (2015) examined the performance of surface classification algorithms, used for the analysis of backscattered microwave and ultrasonic signals. The performance of four common classification algorithms has been analysed for the case of differentiation between the four types of surfaces: asphalt, gravel, grass and sand. The most effective proved to be multilayer estimator (MLP) method based on the use of neural network. The average probability of correct recognition in this case was 99%. It has been demonstrated that k-means method (Euclidean distance) is the least accurate. Plans of research include the optimization of classification methods and increasing the number of surfaces under investigation. In particular, classification of different types of snow and ice covered roads seems to be the most important from a practical point of view.
Analytically, this study is a diagnostic classification. It is a test of how well measurement technology can classify types of road surfaces. Having such technology is useful for rapid collection of data about road surfaces.

Hamdar et al. (2016) characterize the longitudinal driving behavior under different road-geometry and weather conditions, as two factors that significantly affect congestion and safety in transportation systems. A Prospect Theory based car-following model of Hamdar et al. (2008) is extended to capture the behavioral dynamics resulting from these external factors. 15 driving experiments were designed and carried out using the STISIM Drive simulator software. The 66 car-following experiments conducted by 36 drivers were used to calibrate the model using a Genetic Algorithm.

It was found that the overall drivers' average speed, time headway, time to collision, and distance headway are affected by both the roadway-related factors (lane width, shoulder width, median existence, median type, horizontal carves and vertical curves) and weather related factors (foggy weather and icy and wet road surface conditions). It has been confirmed, that undivided road causes

[1] HSM procedure can predict, under specific road geometric conditions, road crash frequencies per year for injuries, fatalities and all casualties.

drivers to adopt an aggressive driving strategy. Traveling on the divided road, conversely, drivers adopt less aggressive behavior. The narrower lanes are also found to be one of the influential factors that impact drivers driving style when following a leader. Drivers driving on the road without hard shoulders are less likely to follow the leader at a dangerously close distance. Inadequate visibility distance is also found to influence driving behavior. Low visibility causes drivers to increase their distance with the leader, while in higher visibility drivers tend to follow the leader more closely. It is evident that driving on slippery road surfaces are much challenging and drivers become much vigilant.
It is observed that parametres reflecting external weather impact, increases as weather condition gets worse. On the other hand, parametres reflecting external road impact, decreases when road condition gets worse. Drivers become more aggressive in dealing with challenging roadway and weather conditions. Drivers tend to underestimate the losses caused by a rear-end collision under extreme conditions and overestimate the crash losses when traveling under normal conditions.

3.1.3 Exploratory analysis of results

Table 3.1: Description of coded studies design

Author(s), Year	Sample and study design	Method of analysis	Outcome indicator	Main result
Amini et al., 2014	32 un-signalized intersections in Teheran, data including accident, traffic and friction coefficient; other variables: operational speed at major and minor roads, mean texture depth (MTD)	Loglinear regression	The effect of pavement surface skid resistance on the safety of urban intersections	Relatively significant effect on the accident rate; 7,5% decrease in accident rate as the friction number increases by 1%
Lee et al., 2015	Roadway, traffic and crash data for the specific information of individual crashes on state-maintained roads for 2012 were collected from FDOT (Florida Department of Transportation)	Random forest model, 6 Bayesian ordered logistic regression models	Efect of pavement conditions on crash severity levels	The speed limits and single/multi –vehicle collision have the largest influence on the severity of traffic crashes.
McCarthy et al., 2015	2010-2012 crash data, 2010-2012 AADT and horizontal radius of curvature for roads in the Salem District of Virginia; skid resistance was measured;	Empirical Bayes, negative binomial regression, Akaike Information Criterion	Crash count data as a function of roadway characteristics	Grip number is statistically significant to the SPF models
Najafi et al., 2015	Urban roads, data provided by New Jersey Department of Transportation; friction measurments collected by a ribbed-tire, locked-wheel skid trailer	Regression analysis	Evaluated effect of friction on car crashes	Friction is significant factor affecting the ratios of wet- and dry- condition car crashes
Buddhavarapu et al., 2015	43 PCF projects, constructed between 2005 and 2009 across the Texas road network; 83 reference road segments were identified	Bayesian before-after safety analysis	Safety effectiveness of PCF (permeable friction course)	PCF is not effective in reducing wet weather crashes; it relies on its interrelationship with the road user
Bystrov et al., 2015	Analysis based on the database, recorded on 500 outdoor locations near Birningham (UK); 4 classification tools: MLE, k-means, KNN and MLP	Analysis of sonar and 24 GHz radar data	Differentiation between 4 types of surfaces: asphalt, gravel, grass and sand.	The most effective proved to be MLP method based on the use of neural network.99% was the average probability of correct recognition

Wei et al., 2011	The quantitative relationship between car-following distance and road roughness, velocity, reaction time et al were induced. The theoretical value of safe distance under different road conditions, such as roads with anti-skid surface, asphalts pavement, rain, snow and ice was explored.	A safety Distance Design Model based on Just Noticeable Difference (JDN).	According to idea of car-following model, the JND was introduced to analyse how the driver apperceives the state of the front vehicle through the change of the headway.	Road conditions are distinguished by adhesion coefficient. It's peak value is much higher for asphalt or concrete pavement than for rainy road, snowy road or icy road. The smoother the road, the greater the minimum safety distance. The road capacity is improved after the anti-skid material is paved. The safety distance depends on the visibility and the slippery of road surface.
Usman et al., 2012	Different collision frequency models are calibrated using hourly data collected from 31 different highway routes across Ontario, Canada; over 6 winter seasons (2000-2006)	Disaggregate modelling approach; multilevel Poisson lognormal model (PLN) and a single level generalized negative binomial model (GNB)	(1) identifying factors, affecting winter road safety; (2) quantifying the effect of winter road maintenance on road collisions during snow storm events	Road surface conditions are identified as one of the major contributing factors, representing the first contribution showing the empirical relationship between safety and road surface conditions at such a disaggregate level.
Fernandes et al., 2014	The analysis of the accident risk as a function of pavement surface properties was carried out by setting admissible accident risk levels to establish threshold values for IFI (International Friction Index), CF (coefficient of friction) and TD (texture depth) in each RE (road environment).	(1) evaluating the influence of the pavement surface properties on road accidents; (2) establishing the threshold values for pavement surface properties	Threshold values for IFI, CF and TD.	There is an increase in the accident risk with the reduction of CF and TD in all REs.
Russo et al., 2016	Crash data collected on two-lane rural roads in Southern Italy; a 5-year period (2006 – 2010); SPFs calibration and then SPFs validation	Negative binomial regression model	SPFs on Road Segments with injuries and fatalities reflecting base geometric conditions	The greatest impact on yearly frequency of crash injuries and fatalities have: L, AADT, LW CI and VG.
Elvik R., 2016	Only chosen risk factors, at least 2 studies performed at least 10 years apart; criteria for studies: 1) successive studies of the same risk factor in the same country; 2) the same or at least highly similar methods; they should refer to the same level of accident or injury severity.	Exploratory study	Stability over time of the association between risk factors and accident occurrence.	The increase in risk associated with driving on a wet road surface during winter has not declined over time but with driving on a snow- or ice-covered road surface has become slightly smaller (Sweden);
Rekila et al., 2016	2 ordinary bicycles, measuring friction in winter condition (April 2014); speed 25 km/h – then braked until a full stop; one test in the morning, one in the afternoon; friction coefficient values were also measured by FMDs before and after the braking test	Test execution: deceleration and braking distance	Measured friction and friction coefficient values, measured by FMDs	Results show a good correlation between the two friction-measuring methods; there is no systematic error between them. The variability of bicycle friction was higher compared to the variability of each individual FMD (friction measurment device).
Walus K.J., 2016	Road test (4 series) after a snowy day, bituminous pavement covered with fresh snow, straight road without the traffic, less than 1% longitudinal inclination	Experimental study	Mean longitudinal accelerations	The lowest values of acceleration on the day with the lowest ambient temperature and temperature of fresh snow –

				this caused a surface freezing of snow and could have generated a higher rolling resistance.
Song et al., 2005	Investigation of possible correlations between skid resistance indicator and influential factor for hot mix asphalt surfaced pavements; Maryland State Highway Administration Pavement Management System; annual network level pavement friction testing from March to November	Regression analysis	Coefficient of determination	The friction number on rural roads is higher than on urban roads. The FN on roadways seems to reaches a steady state condition in about one year after resurfacing.
Hamdar et al., 2016	A driving simulator, 76 driving experiments, 36 students with different driving experience participated in the experiments. Average age was 24.8 years. , average driving experience – 6 years; they were randomly assigned to 2 or 3 of the 15 experimental scenarios (5.5 min each – 3 min of pre-experimental driving and 1.5 min of post-experimental driving). 66 effective results are collected.	After studying the driving trends observed in experiments, the extended Prospect Theory based acceleration model was calibrated using the produced trajectory data.	From the modelling perspective, Prospect Theory based acceleration model's cognitive architecture distinguished two main types of information corresponding to different value functions: the weather-related information and the road-related information.	Parametres, reflecting external weather impact, increases as weather condition gets worse. Parametres, reflecting external road impact, decreases when road conditions gets worse. Drivers become more aggressive in dealing with challenging roadway and weather conditions.

3.1.4 Summarising the results

Coded studies are too heterogenous to perform a meta-analysis. A vote-count analysis would also not be meaningful, because the number of studies covering individual road surface risk factor is too low. Consequently, review-type analysis was selected. Results were also summarized through a qualitative summary table (see Table 3.2).

Skid resistance is one of the most important surface properties with regard to safety.

- *Low friction is associated with higher crash rates (for both, wet- and dry- conditions).*
- *Reduction of coefficient of friction (CF) and texture depth (TD) brings an increase in the accident risk.*
- *Pavement surface skid resistance can improve safety of urban intersections (7.5% decrease in accident rate as the friction number increase by 1%).*

Moreover, skid resistance is one of the factors that determine braking distance and sliding forces in a sharp bend. The skid resistance of an asphalt surfacing decreases continuously with time, due to the polishing action of the traffic. It was found to be a significant factor effecting the ratios of both wet- and dry- condition car crashes on urban roads. Urban roads seem to experience a considerable amount of polishing in the first year after resurfacing. The correlation between friction and traffic intensity on urban roads is very weak. On rural roads, the friction decreases linearly with the natural logarithms of Annual Average Daily Traffic per lane.
Poor pavement condition decreases the severity of single-vehicle collisions on low-speed roads whereas it increases their severity on high-speed roads. On the other hand, the poor pavement condition increases the severity of multiple-vehicle crashes on all roads.

Road conditions are distinguished by adhesion coefficient. The good adhesion coefficient plays a decisive role in preventing a rear-end collision.

- *In the dry case, the adhesion coefficients of concrete pavement and asphalt road are almost the same, but they are much lower after the rain, snow or in icy conditions.*

Winter conditions represent another negative impact on the safety of road users.

- *Even a small increase in slipperiness of section of road can increase the accident rate of the section of road tenfold.*

Icy and wet road surface conditions affect the overall drivers' average speed, time headway, time to collision, and distance headway.

- *It is evident that driving on slippery road surfaces are much challenging and drivers become much vigilant.*

Factors such as visibility, precipitation intensity, air temperature, wind speed, exposure, indicator for month, trend within storm and site-specific factors have statistically significant effects on winter road safety. Road surface conditions were found to have a signification contribution to the variation of collisions within and between individual storms and maintenance routes. The speeds of cars on the highway are usually very high. In order to prevent traffic accidents effectively, the driver should control the speed well. The road conditions are distinguished by adhesion coefficient. The slipping distance of a car is determinated by adhesion coefficient when it brakes and the good adhesion coefficient plays a decisive role in preventing a rear-end collision. In the dry case, the adhesion coefficients of concrete pavement and asphalt road are almost the same, but they show obvious difference after the rain. The minimum safe distances gradually increase with the decreasing friction coefficient.

The size of the effects are difficult to compare across studies, because the effects are mostly expressed as a coefficient. The transferability of results from one country to another is relatively low, especially if countries have a different climate conditions. Studies, which have been coded, come from different countries: UK, Sweden, Portugal, Netherlands, Italy, Poland, Canada, USA, Iran and China.

Table 3.2: Description of coded studies design

Author(s), Year	**Sample and study design**	**Method of analysis**	**Outcome indicator**	**Main result**
Amini et al., 2014	32 un-signalized intersections in Teheran, data including accident, traffic and friction coefficient; other variables: operational speed at major and minor roads, mean texture depth (MTD)	Loglinear regression	The effect of pavement surface skid resistance on the safety of urban intersections	Relatively significant effect on the accident rate; 7,5% decrease in accident rate as the friction number increases by 1%
Lee et al., 2015	Roadway, traffic and crash data for the specific information of individual crashes on state-maintained roads for 2012 were collected from FDOT (Florida Department of Transportation)	Random forest model, 6 Bayesian ordered logistic regression models	Effect of pavement conditions on crash severity levels	The speed limits and single/multi –vehicle collision have the largest influence on the severity of traffic crashes.
McCarthy et al., 2015	2010-2012 crash data, 2010-2012 AADT and horizontal radius of curvature for roads in the Salem District of Virginia; skid resistance was measured;	Empirical Bayes, negative binomial regression, Akaike Information Criterion	Crash count data as a function of roadway characteristics	Grip number is statistically significant to the SPF models

Najafi et al., 2015	Urban roads, data provided by New Jersey Department of Transportation; friction measurments collected by a ribbed-tire, locked-wheel skid trailer	Regression analysis	Evaluated effect of friction on car crashes	Friction is significant factor affecting the ratios of wet- and dry- condition car crashes
Buddhavarapu et al., 2015	43 PCF projects, constructed between 2005 and 2009 across the Texas road network; 83 reference road segments were identified	Bayesian before-after safety analysis	Safety effectiveness of PCF (permeable friction course)	PCF is not effective in reducing wet weather crashes; it relies on its interrelationship with the road user
Bystrov et al., 2015	Analysis based on the database, recorded on 500 outdoor locations near Birmingham (UK); 4 classification tools: MLE, k-means, KNN and MLP	Analysis of sonar and 24 GHz radar data	Differentiation between 4 types of surfaces: asphalt, gravel, grass and sand.	The most effective proved to be MLP method based on the use of neural network.99% was the average probability of correct recognition. The study is a test of how well measurement technology can classify different types of road surfaces. That is useful for rapid collection of data about road surfaces.
Wei et al., 2011	The quantitative relationship between car-following distance and road roughness, velocity, reaction time etc. were induced. The theoretical value of safe distance under different road conditions, such as roads with anti-skid surface, asphalts pavement, rain, snow and ice was explored.	A safety Distance Design Model based on Just Noticeable Difference (JDN).	According to idea of car-following model, the JND was introduced to analyse how the driver apperceives the state of the front vehicle through the change of the headway.	Road conditions are distinguished by adhesion coefficient. It's peak value is much higher for asphalt or concrete pavement than for rainy road, snowy road or icy road. The smoother the road, the greater the minimum safety distance. The road capacity is improved after the anti-skid material is paved. The safety distance depends on the visibility and the slippery of road surface.
Usman et al., 2012	Different collision frequency models are calibrated using hourly data collected from 31 different highway routes across Ontario, Canada; over 6 winter seasons (2000-2006)	Disaggregate modelling approach; multilevel Poisson lognormal model (PLN) and a single level generalized negative binomial model (GNB)	(1) identifying factors, affecting winter road safety; (2) quantifying the effect of winter road maintenance on road collisions during snow storm events	Road surface conditions are identified as one of the major contributing factors, representing the first contribution showing the empirical relationship between safety and road surface conditions at such a disaggregate level.
Fernandes et al., 2014	The analysis of the accident risk as a function of pavement surface properties was carried out by setting admissible accident risk levels to establish threshold values for IFI (International Friction Index), CF (coefficient of friction) and TD (texture depth) in each RE (road environment).	(1) evaluating the influence of the pavement surface properties on road accidents; (2) establishing the threshold values for pavement surface properties	Threshold values for IFI, CF and TD.	There is an increase in the accident risk with the reduction of CF and TD in all REs.
Russo et al., 2016	Crash data collected on two-lane rural roads in Southern Italy; a 5-year period (2006 – 2010); SPFs calibration and then SPFs validation	Negative binomial regression model	SPFs on Road Segments with injuries and fatalities reflecting base geometric conditions	The greatest impact on yearly frequency of crash injuries and fatalities have: L, AADT, LW CI and VG.

Elvik R., 2016	Only chosen risk factors, at least 2 studies performed at least 10 years apart; criteria for studies: 1) successive studies of the same risk factor in the same country; 2) the same or at least highly similar methods; they should refer to the same level of accident or injury severity.	Exploratory study	Stability over time of the association between risk factors and accident occurrence.	The increase in risk associated with driving on a wet road surface during winter has not declined over time but with driving on a snow- or ice-covered road surface has become slightly smaller (Sweden);
Rekila et al., 2016	2 ordinary bicycles, measuring friction in winter condition (April 2014); speed 25 km/h – then braked until a full stop; one test in the morning, one in the afternoon; friction coefficient values were also measured by FMDs before and after the braking test	Test execution: deceleration and braking distance	Measured friction and friction coefficient values, measured by FMDs	Results show a good correlation between the two friction-measuring methods; there is no systematic error between them. The variability of bicycle friction was higher compared to the variability of each individual FMD (friction measurment device). Bicycling is becoming a more and more common mode of transportation in European cities. Winter conditions create a challenge for providing a high quality, functional bicycle network. If we want to set standards for winter maintenance of cycleways, this also includes a friction criterion.
Walus K.J., 2016	Road test (4 series) after a snowy day, bituminous pavement covered with fresh snow, straight road without the traffic, less than 1% longitudinal inclination	Experimental study	Mean longitudinal accelerations	The lowest values of acceleration on the day with the lowest ambient temperature and temperature of fresh snow – this caused a surface freezing of snow and could have generated a higher rolling resistance.
Song et al., 2005	Investigation of possible correlations between skid resistance indicator and influential factor for hot mix asphalt surfaced pavements; Maryland State Highway Administration Pavement Management System; annual network level pavement friction testing from March to November	Regression analysis	Coefficient of determination	The friction number on rural roads is higher than on urban roads. The FN on roadways seems to reaches a steady state condition in about one year after resurfacing. The result of the study shows difference of friction between urban roads and rural roads which reveals that traffic fashion (speed, stopping frequency and etc.) would play a more important role than traffic intensity in the polishing of surface.
Hamdar et al., 2016	A driving simulator, 76 driving experiments, 36 students with different driving experience participated in the experiments. Average age was 24.8 years. , average driving experience – 6 years; they were randomly assigned to 2 or 3 of the 15 experimental scenarios (5.5 min each – 3 min of pre-experimental driving and 1.5 min of post-experimental driving). 66 effective results are collected.	After studying the driving trends observed in experiments, the extended Prospect Theory based acceleration model was calibrated using the produced trajectory data.	From the modelling perspective, Prospect Theory based acceleration model's cognitive architecture distinguished two main types of information corresponding to different value functions: the	Parametres, reflecting external weather impact, increases as weather condition gets worse. Parametres, reflecting external road impact, decreases when road conditions gets worse. Drivers become more aggressive in dealing with challenging roadway and weather conditions.

			weather-related information and the road-related information.	

3.1.5 Full list of studies

Table 3 Final list of coded studies, and reason to exclude studies that should have been coded

Authors	Title	Year	Country	Status	Reason of exclusion
Buddhavarapu, Smit, Prozzi	A full Bayesian before-after analysis of permeable friction course (PFC) pavement wet weather safety	2015	United States	Coded	
Najafi, Flintsch, Medina	Linking roadway crashes and tire-pavement friction: a case study	2015	United States	Coded	
McCarthy, Flintsch, Katicha, McGhee, Medina-Flintsch	A new approach for managing pavement friction and reducing road crashes	2016	United States	Coded	
Lee, Nam, Abdel-Aty	Effects of Pavement Surface Conditions on Traffic Crash Severity	2015	United States	Coded	
Bystrov, Abbas, Hoare, Tran, Clarke, Gashinova, Cherniakov	Analysis of Classification Algorithms Applied to Road Surface Recognition	2015	United Kingdom	Coded	
Freeman, Neyens, Wagner, Switzer, Alexander, Pidgeon	A video based run-off-road training program with practice and evaluation in a simulator	2015	United States	Not coded	Nor relevant
Rekila, Klein-Paste	Measuring bicycle braking friction in winter conditions	2015	Norway	Coded	
Elvik	Does the influence of risk factors on accident occurrence change over time?	2016	Norway, Denmark, USA, Sweden	Coded only road surface conditions	
Freeman, Jensen, Wagner, Alexander	A Comparioson of Multiple Control Strategies for Vehicle Run-Off-Road and Return	2015	United States	Not coded	Not relevant
Wei, Yanfang, Xingli	A Safety Distance Design Model Based on Just Noticeable Difference	2011	China	Coded	
Usman, Fu, Miranda-Moreno	A disaggregate model for quantifying the safety effects of winter road maintenance activities at an operational level	2012	Canada	Coded	
Fernandes, Neves	Threshold values of pavement surface properties for maintenance purposes based on accidents modelling	2013	Portugal	Coded	
Van Petegem, Wegman	Analyzing road design risk factors for run-off-road crashes in the Netherlands with crash prediction models	2014	Netherlands	Coded	Not relevant
Russo, Busiello, Dell'Acqua	Safety performance functions for crash severity on undivided rural roads	2016	Italy	Coded	
Amini, Beigi	Modeling the Effect of Road Surface friction on the Accident Rate of Urban Un-Signalized Intersections	2014	Iran	Coded	
Song, Chen, Smith, Hedfi	Investigation of Hot Mix Asphalt Surfaced Pavements Skid Resistance in Maryland State Highway Network System	2005	United States	Coded	
Saltan, Özgüngördü, Özen	An Environmental Method against Icing for Road Pavements I-Development of Test Equipment and Procedure	2012	International	Not coded	Not relevant
Hamdar, Qin, Talebpour	Weather and road geometry impact on longitudinal driving behaviour: Exploratory analysis using an empirically supported acceleration modelling framework	2016	United States	Coded	

Walus	**The intensity of the acceleration and deceleration of a passenger car on a road surface covered with fresh snow**	**2016**	**Poland**	**Coded**	

Coded studies (sorted by author)

Amini B., Beigi H.H.A (2015). Modeling the Effect of Road Surface friction on the Accident Rate of Urban Un-Signalized Intersections, TRB 2015 Annual Meeting.

Buddhavarapu P., Smit A.F., Prozzi J.A. (2015). A fully Bayesian before-after analysis of permeable friction course (PFC) pavement wet weather safety, Accident Analysis and Prevention, Volume 80, 89-96

Bystrov A., Abbas M., Hoare E., Tran T.Y., Clarke N., Gashinova M., Cherniakov M. (2015). Analysis of Classification Algorithms Applied to Road Surface Recognition, IEEE 2015.

Elvik R. (2016). Does the influence of risk factors on accident occurrence change over time?, Accident Analysis and Prevention, Volume 91, 91-102.

Fernandes A., Neves J. (2014). Threshold values of pavement surface properties for maintenance puproses based on accidents modelling, International Journal of Pavement Engineering, Vol. 15, 917-924.

Hamdar S.H., Qin L., Talebpour A. (2016). Weather and road geometry impact on longitudinal driving behaviour: Exploratory analysis using an empirically supported acceleration modelling framework, Transportation Research Part C 67, 193-213.

Lee J., Nam B., Abdel-Aty M. (2015). Effects of Pavement Surface Conditions on Traffic Crash Severity, American Society of Civil Engineers.

McCarthy R., Flintsch G.W., Katicha S.W., McGhee K.K., Medina-Flintsch A. (2016). A new approach from managing pavement friction and reducing road crashes, TRB 2016 Annual Meeting.

Njafi S., Flintsch G.W., Medina A. (2015). Linking Roadway crashes and tire-pavement friction: a case study, International Journal of Pavement Engineering (IJPE).

Rekilä K.P., Klein.Paste A. (2016). Measuring bycicle braking friction in winter conditions, Cold Regions and Technology 125, 108-116.

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Synopsis 8:

Adverse weather conditions – Rain

1 Summary

Nathalie Focant, Heike Martensen (August 2016)

Colour Code Yellow

Rain has been consistently shown to be a risk factor in the sense that the accident rate (the number of crashes per vehicle or km-driven) is higher in the rain than in comparable situations without rain. This has however, mainly been tested with motorvehicles, and it is not clear whether it is true for other road users as well.

1.1 ABSTRACT

Rain has been consistently shown to be a risk factor (in Europe) in the sense that the **injury crash rate** (the number of crashes per vehicle or km-driven) is higher in the rain than in comparable situations without rain. This has however, mainly been tested with motor vehicles, and it is not clear whether it is true for other road users as well. The effect on fatal or severe crashes is less reliable and crashes in rainy conditions have been found to be less severe (except in Scandinavian countries).
The **net-effect on crash occurrence** can differ substantially from the risk effect of rain, because adverse weather conditions also affect the mobility, in particular for vulnerable road users who are more exposed to the weather. Consequently the net effect of crash occurrence yields much more mixed results with decreases in crash numbers observed more often for vulnerable road users and in urban areas. More research is needed to disentangle risk-effects and mobility-effects for vulnerable road users.

1.2 BACKGROUND

1.2.1 What is the effect of rain on road safety?

When looking at the effect of rain, it is important to differentiate between the crash *risk* that is associated with rainfall and the *net-effect* on the number of crashes.
In terms of **risk of crash**, two crucial elements for security are undermined by the rain: the visibility (through the rain itself, but also the splashing water, the condensation on windscreen, etc.) and grip (through reduced friction of the road surface). Studies indicate that road users seem to adjust their behaviour (reduced speed, less frequent overtaking, etc.), but the changes in driving behaviour are, apparently, insufficient to compensate for the greater risk during bad weather.
Rainfall does also affect the **exposition to this risk**, i.e. the mobility and its characteristics. Weather, and particularly rain, influence which trips are made, the departure time, the travel mode, the itinerary, etc. This concerns in particular two-wheelers and pedestrians, and leisure time trips. These changes to the traffic volume can be so strong, that even with an increase in risk the observed number of crashes can be reduced in rainy conditions.

1.2.2 What is the effect of rain on crash type?

SafetyCube crash scenarios reveal that the percentage of head-on collisions is higher under rainy condition than under dry ones.This is also the case of single crashes, in particular the ones on road. On the opposite, the share of bicycle crashes is smaller under rainy weather.

1.2.3 How is the effect of rain studied?

The present overview focusses on recent (from 1990 to current) studies in European studies. The majority of the studies have employed a multivariate model, in particular time-series models. The variation of the number of crashes over time is explained by different possible factors, such as calendar variables, interventions like new road safety laws and a large variation of weather variables. Rain is often included in the model as one of these possible explanatory variables, and this under one or another form: amount of rainfall, rainfall duration, the presence of rain, etc. If the traffic volume is included (or some proxy for it, e.g. oil sales, number of toll-tickets) into the analysis model, the results measure the effect of rain on the *crash risk*. Otherwise, the results measure the net-effect on the number of crashes or injuries.

1.3 OVERVIEW OF RESULTS

1.3.1 Main results

14 key studies establishing the risk and the net effect of rain in European countries have been examined and a vote-count analysis has been conducted. A total number of 84 effects of rain are reported in the selected studies: 32 on crash/victim risk and 52 on crash/victim occurrence.

Table 1 Percentage of significant positive effects

Impact on risk			**Impact on occurrence**		
Fatal (and severely injured)	Injury	All	Fatal (and severely injured)	Injury	All
85%	100%	94%	38%	54%	46%

Here are the main conclusions:

- The risk to have an injury crash is generally increased when it rains: all coded effects were significant.
- The effect on fatal or severe crashes is less reliable, but still 85% of the studies have found a significant increase in the risk for fatal crashes.
- There is no strong evidence for a greater impact of rain on less severe crashes.
- The net effect on crash-occurrence (or injuries resulting from crashes) is much more mixed. The effect on crash occurrence also differs per road user type.
- The crash risk is consistently found to increase in rain, independently of the type of road (all road-types, rural roads, motorways) tested.
- The net effect of rain on crash occurrence is an increasing one for motorways and rural roads. Tests that included all road types or only urban roads show much more mixed results, however.

1.3.2 Transferability

Although the risk-effect of rain (at least on car occupants) seems to be confirmed in most studies, many variables are likely to play a role for the total effect (for examples, the frequency of rain (might influence compensatory behaviour), the modal share of weather-sensitive modes like cycling and walking or the quality of the road-surface). In this sense, the transferability of results from one country to another is relatively low, especially if countries have a different climate or share of road users.

1.4 NOTES ON ANALYSIS METHODS

There is a relatively large body of studies that have looked at the crash risk and the net-effect for all road users together (total number of crashes/injuries), and which have thus mainly evaluated the effect of rain on car crashes. Few studies have attempted to distinguish the effect by type of user.

However, these few studies have shown that the (net-) effect for pedestrians, cyclists, and motorcyclists (in particular) differs dramatically from those for car-occupants. For these modes, studies that disentangle the risk effect and the effect due to changes in traffic volume are lacking.

2 Scientific overview

2.1 LITERATURE REVIEW

2.1.1 What is the effect of rain on road safety?

When looking at the effect of rain, it is important to differentiate between the crash *risk* that is associated with rainfall and the *net-effect* on the number of crashes.

In terms of **risk of crash**, two crucial elements for security are undermined by the rain: the visibility and grip. The rain itself causes a reduced visibility, especially when it is intense. But splashing water, particularly from lorries, and condensation on windscreen may also increase the problem. Furthermore, the rain reduces the friction of the road surface, which can lead the vehicle to lose the contact with the road (aquaplaning) and, ultimately the driver to lose the control of his vehicle.

At the same time road users seem to adjust their behaviour, in order to compensate for these problems: "*they overtake less, they drive slower and they increase their following distance. However, the risk of a crash during rain is still greater than in dry weather. The changes in driving behaviour are, apparently, insufficient to compensate for the greater risk during bad weather*" (SWOV, 2012).

However, it has been found that the risk of a fatal crash is less increased due to rain as compared to the risk of an injury crash, suggesting that while the risk is increased the severity of the crashes is decreased. This suggests that the change in user's behaviour somehow pays off after all.

Some analyses showed that the risk of rain rises rapidly when it has been dry for a while. For instance, Brodsky & Hakkert (1988) found a dramatic increase in risk after more than two dry days in Israel. In other countries (e.g., Belgium), this effect was not found (Brijs et al., 2008). One explanation for the "lagged effect of rain" (the expert term for the first occurrence of rain after a dry period) could be that the adaptive behaviour of road users needs some time to develop. Another reason could be the dust that collects in dry periods and is turned into slippery mud by the first rain. Both reasons would be very dependent on the general climate and it is conceivable that neither of them apply to a country with marine-climate where long hot periods are rare and road users are basically always prepared to encounter rain.

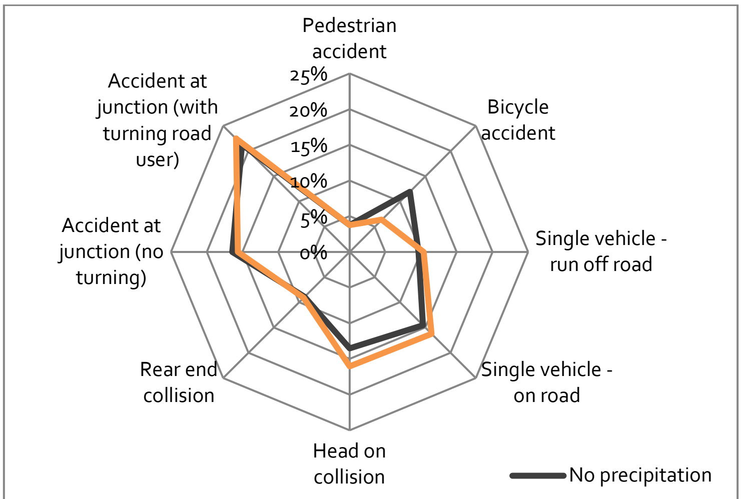
Rainfall does however, not only affect the risk to have an crash, but also the **exposition to this risk**, i.e. the mobility and its characteristics. Weather, and particularly rain, influence which trips are made, the departure time, the travel mode, the itinerary, etc. In case of rain, for example, excursions might be postponed, or done by car instead of on foot or by (motor)bike. This concerns in particular two-wheelers and pedestrians who are more hindered by the rain, as they are not protected by a bodywork. Moreover it also concerns leisure time trips more than work-related ones, which are usually mandatory. These changes to the traffic volume can be so strong, that even with an increase in risk the observed number of crashes can be reduced in rainy conditions.

2.1.2 Crash scenarios

SafetyCube crash scenarios allow to compare crashes in rainy conditions to those in dry/clear conditions (Figure 1).

This crash scenario analysis was conducted using cases from the German In-Depth Accident Study (GIDAS) database. All crashes were considered which were ready for analysis and which were collected in the years 2007 to 2015. In total, records from 14.398 crashes which occurred in the regions of Hannover and Dresden were analysed. The GIDAS database details those crashes which occurred on a public road where at least one person was injured. The crashes are collected according to a statistical sampling process to ensure a high level of representativeness of the actual accident situation in the sample regions. The data collection is conducted using the "on the scene" approach where all factors which were present at a crash are recorded. This does not mean that the recorded factor was a contributory factor towards the crash. For the current analysis all crashes where rain was listed as present at the crash scene were compared to all crashes where no type of precipitation was present at the crash scene.

Figure 1 Share of the different crash types under rain and "no precipitation" weather



Source: GIDAS, 2016

Under rainy conditions the percentage of head-on collisions is higher than under dry ones.This is also the case of single crashes, in particular the ones on road. This could be the consequence of an increase number of losses of vehicle control, probably due to the reduced grip. On the opposite, the share of bicycle crashes is smaller under rainy weather, what surely reflects the reduced traffic of two-wheelers in such conditions.

2.2 DESCRIPTION OF STUDIES

2.2.1 How is the effect of rain studied?

For the present overview the focus is on recent (from 1990 to current) studies in European studies and the majority of the studies have employed a multivariate model, in particular time-series models. The variation of the number of crashes over time is explained by different possible factors, such as calendar variables, interventions like new road safety laws and a large variation of weather variables. Rain is often included in the model as one of these possible explanatory variables, and this under one or another form: amount of rainfall, rainfall duration, the presence of rain, etc. *Source GIDAS, 2016*

It is essential whether the *traffic volume* is included into the analysis model. If the traffic volume is included (or some proxy for it, e.g. oil sales, number of toll-tickets) then the results measure the effect of rain on the *crash risk*. If it is not included, then the results measure the *net-effect* on the number of crashes or injuries. In three studies, the dependent variable is crash severity.

2.2.2 How well has the effect of rain been studied?

There is a relatively large body of studies that have looked at the crash risk and the net-effect for all road users together (total number of crashes/injuries), and which have thus mainly evaluated the effect of rain on car crashes. Few studies have attempted to distinguish the effect by type of user. However, these few studies have shown that the (net-) effect for pedestrians, cyclists, and motorcyclists (in particular) differs dramatically from those for car-occupants. For these modes studies that disentangle the risk effect and the effect due to changes in traffic volume are lacking.

2.2.3 Transferability

The size of the effects are difficult to compare across studies, because the effects are mostly expressed as a coefficient in a multivariate model, which vary a lot with respect to model-architecture and other variables included.
Although the risk-effect of rain (at least on car occupants) seems to be confirmed in most studies, many variables are likely to play a role for the total effect. For example:

- the frequency of rain (might influence compensatory behaviour)
- the modal share of weather-sensitive modes like cycling and walking
- the laws and use of day-time running lights
- the quality of the road-surface
- the use of reflective items by vulnerable road users

In this sense, the transferability of results from one country to another is relatively low, especially if countries have a different climate or share of road users. This is particularly why studies on Athens Region indicate a positive effect of rain on road safety (fewer injury crashes) (see in particular Karlaftis & Yannis, 2010 and Bergel & al. 2013).

2.3 DESCRIPTION OF ANALYSIS CARRIED OUT

2.3.1 Vote-count analysis

14 key studies establishing the risk and the net effect of rain in European countries have been coded, analysed and summarized. While most studies used multivariate methods to estimate the effect of rain, the model architecture and included variables differ too much between studies to allow a meta-analysis of the results. Instead a vote-count analysis has been conducted: each test that is executed in one of the studies (or more specifically each coefficient) has one vote on the effect of rain. The results are coefficients and a positive coefficient indicates an increase of the dependent variable when it rains and a negative coefficient a decrease. Of course the coefficient can also be non-significant (which means usually that it has been excluded from the final model). Consequently, the vote can take three different values:

- An increase in either in crash occurrence, the number of victims, or the crash risk (↗)
- A decrease (↘)
- No significant difference (-)

These vote-counts are analysed with respect to different characteristics of the dependent variables: net-effect versus impact on risk, outcome severity, road user type, type of road). Whether the analyses are based on victim counts or crash counts seems to make very little difference. This variable is therefore not taken up in the following analyses, which are aggregated over effects found on victim numbers and effects found on crash numbers.

A total number of 84 effects of rain are reported in the selected studies: 32 on crash/victim risk and 52 on crash/victim occurrence.

2.3.2 Crash-risk and crash occurrence

Table 2 Results for risk and crash-occurrence by outcome severity

	Total number of effects tested	Result (number of effects)			Result (% of effects)	
		↗	-	↘	↗	↘
Risk	**32**	**30**		**2**	**94%**	**6%**
Fatal (and severely injured)	13	11		2	85%	15%
Injury	19	19			100%	0%
Crash Occurrence	**52**	**24**	**10**	**18**	**46%**	**35%**
Fatal (and severely injured)	24	9	5	10	38%	42%
Injury	28	15	5	8	54%	29%

The *risk* to have an injury crash is generally increased when it rains: all coded effects were significant. The effect on fatal or severe crashes is less reliable, but still 85% of the studies have found a significant increase in the risk for fatal crashes.

The *net-effect* on crash-occurrence (or injuries resulting from crashes) is much more mixed. 23 tested effects indicated an increase of crashes when it rains, 19 effects were decreases, and 11 tests had non-significant results. Again, the effects for all injury crashes were more likely to be significant increases than the studies that have looked at severe crashes only (fatal crashes or crashes with killed or severely injured victims).

2.3.3 Crash occurrence by road user type

Table 3 Results for risk and crash-occurrence by road user type tested

	Total number of effects tested	Result (number of effects)			Result (% of effects)	
		↗	-	↘	↗	↘
Risk	**32**	**30**		**2**	**94%**	**6%**
All	29	27		2	93%	7%
Car	2	2			100%	0%
Cyclist & Pedestrian	1	1			100%	0%
Crash Occurrence	**52**	**24**	**10**	**18**	**46%**	**35%**
All	23	15	4	4	65%	17%
Car	4	2	1	1	50%	25%
Motor vehicle	2			2	0%	100%
Goods vehicle	6	2	1	3	33%	50%
Cyclist	4	1		3	25%	75%
Moped	3	2	1		67%	0%
Moto	4	1		3	25%	75%
Pedestrian	6	1	3	2	17%	33%

In Table 3 it can be seen that the *risk* associated with rain has mostly been tested on all crash outcomes or on car-crashes. Only one study reported specifically results for pedestrians. The proxy for traffic volume used in that study (oil sales) does however not concern pedestrian activity

(Fridstrom, 1991). Consequently there are no risk estimates yet for the effect of rain on vulnerable road users.

The *net-effect* of rain on crash occurrence per road user type has very mixed results. Among the tests of the effect of rain on total crash-occurrence (i.e. all road users), more than half revealed significant increases of crash occurrence (and most of the others were non-significant). For some road user types, like cyclists and motorcyclists, the results seem to point to a decrease in crash numbers when it rains. This also seems to be the case for goods vehicles – which is much less intuitive. While for two wheelers it is conceivable that a strong reduction of exposure under rainy conditions could offset an increase in risk, for goods vehicle the exposure cannot be expected to be strongly influenced by rain, and there are no obvious reasons why the factors that lead to an increase in risk for car-occupants (visibility, friction) should apply less to occupants of goods vehicles.

It is clear that more systematic research is needed here, disentangling the effect of rain on exposure to that on the crash risk for each road user type separately.

2.3.4 Crash risk and crash occurrence by road type

Table 4 Results for risk and crash-occurrence by road type

	Total number of effects tested	Result (number of effects)			Result (% of effects)	
		↗	-	↘	↗	↘
Risk	**32**	**30**		**2**	94%	6%
All	20	18		2	90%	10%
Motorway	6	6			100%	0%
Rural	6	6			100%	0%
Crash Occurrence	**52**	**24**	**10**	**18**	**46%**	**35%**
All	42	15	10	17	36%	40%
Motorway	2	2			100%	0%
Rural	4	4			**100%**	**0%**
Urban	4	3		1	75%	25%

The *crash risk* is consistently found to increase in rain, independently of the type of road (all road-types, rural roads, motorways) tested. It must be noted however, that there are no studies that established the risk effect in urban areas.

The *net-effect* of rain on crash occurrence is an increasing one for motorways and rural roads. Tests that included all road types or only urban roads show much more mixed results, however. Decreasing crash numbers in rainy conditions are found somewhat more often than increasing ones.

2.3.5 Crash severity

Although rain effects on injury crashes are more often found to be significant than for fatal crashes, this could also be an artefact of the larger sample size that is usually available for the much more frequent injury crashes. Only three studies have actually addressed this issue directly and 2 out of 3 found a significant decrease in crash severity in rainy conditions. For 15 tests reported in the same way for injury crashes and fatal crashes both results (larger effect for fatal crashes or larger effect for injury crashes) were approximately equally frequent. So the direct evidence for a greater impact of rain on less severe crashes is not very strong. It should be noted, however, that almost all results against this hypothesis came from two Scandinavian studies.

2.4 CONCLUSION

The 14 key studies establishing the risk and the net effect of rain in European countries have been coded, analysed and summarized. While most studies used multivariate methods to estimate the effect of rain, the model architecture and included variables differ too much between studies to allow a meta-analysis of the results. Instead a vote-count analysis has been conducted.

The risk to have an injury crash is generally increased when it rains: all coded effects were significant. The effect on fatal or severe crashes is less reliable and crashes in rainy conditions have been found to be less severe (except in Scandinavian countries).

The net-effect on crash occurrence can differ substantially from the risk effect of rain, because adverse weather conditions also affect the mobility, in particular for vulnerable road users who are more exposed to the weather. Consequently the net effect of crash occurrence yields much more mixed results with decreases in crash numbers observed more often for vulnerable road users and in urban areas.

While the risk of rain for motorized traffic is relatively well studies, more research is needed to disentangle risk-effects and mobility-effects for vulnerable road users.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature search strategy

Principles

As researches studying the impact of adverse weather on road safety are usually not limited to one meteorological factor, the literature search was conducted together for the three conditions of adverse weather selected for the SafetyCube project (rain, snow/frost and wind).

Excluded:

- effect of climate change
- impact on crashes in tunnels
- impact on mobility, traffic/transport/flow, driver's behaviour (speed, etc.), vehicle's behaviour (deviation, etc.)
- evaluation of countermeasures (wind fences, tires, road maintenance, education, weather information systems, speed limit, asphalt composition, etc.)
- effect of road surface conditions
- studies that answer to the question "in which conditions is the rain/snow/wind the more risky?"

Research terms and hits

Database: Scopus **Date:** 7th and 8th of April 2016

Limitations/ Exclusions:

- Search field: TITLE-ABS-KEY
- Published: 1990 to current
- Document Type: ALL
- Subject Area: ALL

	search no.	search terms / operators / combined queries	hits
snow	#1	(TITLE-ABS-KEY (snow OR ice OR temperature OR hail OR frost) AND TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities"))	620
	#2	(TITLE-ABS-KEY (snowfall) AND TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities")	23
wind	#1	KEY (wind) AND KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident")	40
	#2	KEY (wind) AND KEY ("accident risk" OR "crash risk")	20
	#3	(TITLE-ABS-KEY (wind) AND TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk"))	149
rain	#1	TITLE-ABS-KEY (rain OR precipitation) AND TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk")	186
	#2	TITLE-ABS-KEY (rainfall) AND TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk")	64

Database: TRID **Date:** 7th and 8th of April 2016

Limitations/ Exclusions:

- Published: 1990 to 2016
- Document source : ALL, Document Type: ALL, Subject area : ALL
- Language: English and French

	search no.	search terms / operators / combined queries	hits
snow	#1	Snow "road safety"+ snow "road accident" + snow "accident risk"	387 + 42 + 37
	#2	ice "road safety"+ ice "road accident" + ice "accident risk"	296 + 36 + 24
	#3	temperature "road safety"+ temperature "road accident" + temperature "accident risk"	222 +24 + 12
	#4	hail frost "road safety" "+ hail frost "road accident" + hail frost "accident risk"	52
	#5	Neige/glace/gel/verglas/température/grêle "sécurité routière »	36
wind	#1	wind, "road safety"	123
	#2	wind "road accident"	8
	#3	wind "accident risk"	16
	#4	Vent "sécurité routière"	15
rain	#1	rain "road safety" / precipitation "road safety"	153 + 81
	#2	rain "road accident" / precipitation "road accident"	19 + 18
	#3	rain "accident risk" / precipitation "accident risk"	30 + 24
	#4	Pluie "sécurité routière"/ précipitations "sécurité routière"	26 + 5

Database: ScienceDirect **Date:** 7th and 8th of April 2016

Limitations/ Exclusions:

- Search field: Abstract, title, keywords
- Published: 1990 to current
- Document Type: ALL
- Subject Area: ALL

	search no.	search terms / operators / combined queries	hits
snow	#1	TITLE-ABSTR-KEY(snow OR ice OR temperature OR hail OR frost OR snowfall) and TITLE-ABSTR-KEY("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities").	49
wind	#1	TITLE-ABSTR-KEY(wind) and TITLE-ABSTR-KEY("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk").	127
rain	#1	TITLE-ABSTR-KEY(rain OR precipitation) and TITLE-ABSTR-KEY("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk")	34
	#2	TITLE-ABSTR-KEY(rainfall) and TITLE-ABSTR-KEY("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk").	19

Database: Google Scholar **Date:** 7th and 8th of April 2016

Limitations/ Exclusions:

- Published: 1990 to current
- Document Type: ALL
- Sorted by relevance

	search no.	search terms / operators / combined queries	hits
snow	#1	snow "road safety"	7300 first 5 results pages only
	#2	Snowfall "road safety"	17500 first 5 results pages only
	#3	Frost ice "road safety"	827 first 5 results pages only
	#4	Temperature "road safety"	11900 first 5 results pages only
wind	#1	wind AND ("road accident" OR "road crash" OR "road fatalities" OR "road safety")	10200 first 5 results pages only
rain	#1	(rain OR rainfall OR precipitation) AND ("road accident" OR "road crash" OR "road fatalities" OR "road safety")	14800 first 10 results pages only
	#2	impact of rainfall on road crashes	17500 first 5 results pages only

Database: iRAP toolkit, iRAP website and CEDR website **Date:** 7th and 8th of April 2016

Nothing interesting

Results Literature Search

Database	Hits
Scopus (remaining papers after several limitations/exclusions)	1102
TRID	1686
ScienceDirect	229
Google Scholar	40 results pages
Total number of studies to screen title	3017 + google

Screening

Total number of studies to screen title (in order to evaluate the relevance to the topic)	3017 + google
Number of articles remaining after screening of the title **= Total number of studies to screen abstract**	182
Remaining studies after abstract screening	110

Reference lists also screened:

Andrey J., Mills B., Leahy M., Suggett J.	*Weather as a chronic hazard for road transportation in Canadian cities*	*2003*
Karlaftis, Matthew G Yannis, George	*Weather Effects on Daily Traffic Accidents and Fatalities: Time Series Count Data Approach*	*2010*
KEITH K. KNAPP, LELAND D. SMITHSON, AND AEMAL J. KHATTAK	*Mobility and safety impacts of winter storm events in a freeway environment*	*2000*
Maze T.H., Agarwal M., Burchett G.	*Whether weather matters to traffic demand, traffic safety, and traffic operations and flow*	*2006*
Paul A. Pisano, Lynette C. Goodwin, Michael A. Rossetti	*US highway crashes in adverse road weather conditions*	*2004*
Qiu L., Nixon W.A.	*Effects of adverse weather on traffic crashes: Systematic review and meta-analysis*	*2008*
Strong C.K., Zhirui Y., Shi X.	*Safety effects of winter weather: The state of knowledge and remaining challenges*	*2010*
Swov factsheet	*The influence of weather on road safety*	*2009*
Theofilatos A., Yannis G.	*A review of the effect of traffic and weather characteristics on road safety*	*2014*

Total number of additional relevant articles identified in these reference lists: 12

Removed articles: 15

- 5, due to unspecified weather factors in the summary, and not found pdf
- 10, reviewing article (could be useful for summary)

Total number studies to screen full-text : 107

- **21 addressing "wind" (W) factor**
- **37 addressing "snow" (S) factor**
- **84 addressing "rain" (R) factor**

Prioritizing Coding

Prioritization:

1. Sorting of the papers according to their capability to answer the question "to what extent does this factor impact the number / frequency / severity of road crashes / victims?"
2. Priority to Meta-analyse
3. Among all "very high prior" papers, selection of studies from Europe

Following these prioritization criteria, the full-text screening of the 107 studies has allowed to select 10 papers to be coded.

Table 5 Final list of coded studies, and reason to exclude studies that should have been coded

Authors	Title	Year	Country	Status	Reason of exclusion
Elvik, Fridstrøm, Kaminska, Meyer	**Effects on accidents of changes in the use of studded tyres in major cities in Norway: A long-term investigation**	**2013**	**Norway**	**Coded**	
Fridstrøm	Piggfrie dekk i de største byene	2000	Norway	Not coded	Included in Elvik, Fridstrøm, Kaminska, Meyer (2013)
Elvik, Kaminska	Effects on accidents of reduced use of studded tyres in Norwegian cities	2011	Norway	Not coded	Included in Elvik, Fridstrøm, Kaminska, Meyer (2013)
Elvik	Does the influence of risk factors on accident occurrence change overtime?	2016	Norway	Not coded	No indication on how risk is calculated
Bergel, Rattaire, Aron, Doucet, Violette	**Added risk in case of rain: some recent results for France**	**2011**	**France**	**Coded**	
Aron, Bergel, Saint Pierre, Violette	Added Risk by Rainy Weather on the Roads of Normandie-Centre Region in France	2007	France	Not coded	More or less included in Bergel (2011)
Saint Pierre, Aron, Bergel, Violette	Rain Reconstruction from Various Weather-Related Data Sets Using Logistic Regression: Methodology and Applications	2007	France	Not coded	Methodologic – Does not explain impact of weather on road safety
Bergel, Depire	**Climate, Road Traffic and Road Risk: An Aggregate Approach**	**2004**	**France**	**Coded**	**Close to Bergel (2013) Part one, but more detailed**
Bergel-Hayat, Debbarh, Antoniou, Yannis	**Explaining the road accident risk: Weather effects [PART ONE – Average weather]**	**2013**	**France, Netherlands, Greece**	**Coded**	**Extension of Bergel (2004) to the Netherlands and Athens**
Bergel, Debbarh	Modelling the weather effects on the numbers of injury accidents at an aggregate level in different region (SafetyNet)	2008	France, Netherlands, Greece	Not coded	Included in Bergel (2013)
Bergel, Debbarh, Antoniou, Yannis	**Explaining the road accident risk: Weather effects [PART TWO & THREE – Extreme weather]**	**2013**	**Greece**	**Coded in 2 code-sheets**	
Antoniou, Yannis, Katsohis,	Impact of meteorological factors on the number of injury accidents	2013	Greece	Not coded	Mainly methodologic
Yannis, Antoniou, Katsochis, Papadimitriou	Impact of meteorological variables on the number of injury accidents and fatalities in the Athens region (SafetyNet)	2008	Greece	Not coded	More or less included in Bergel 2013
Hermans, Wets, Van Bossche	**Describing the evolution in the number of highway deaths by decomposition in exposure, accident risk, and fatality risk**	**2006 a**	**Belgium**	**Coded**	
Hermans, Wets, Van Bossche	**Frequency and severity of Belgian road traffic accidents studied by state-space methods + The frequency and severity of road traffic accidents investigated on the basis of state space methods**	**2006 b**	**Belgium**	**Coded**	
Van den Bossche, Wets, Brijs	A Structural Road Accident Model for Belgium	2003	Belgium	Not coded	Completed with/by Van den Bossche (2004)
Van den Bossche, Wets, Brijs	A Regression Model with ARIMA Errors to Investigate the Frequency and Severity of Road Traffic Accidents	2004	Belgium	Not coded	Same data as Hermans (2006 – Frequency), but other methods
Van den Bossche, Wets, Brijs	The role of exposure in the analysis of road accidents : a Belgian case-study	2005	Belgium	Not coded	Too close to Hermans (2006 – Describing)
Focant, Martensen	**Are there more accidents in the rain? Exploratory analysis of the influence of weather conditions on the number of road accidents in Belgium**	**2014**	**Belgium**	**Coded**	
Martensen, Focant,	**Let's talk about the weather. Interpretation of short term**	**2016**	**Belgium**	**Coded**	

Diependaele	**changes in road accident outcomes**				
Fridstrøm, Ingebrigtsen	**An aggregate accident model based on pooled, regional time-series data**	**1991**	**Norway**	**Coded**	
Fridstrøm, Ifver, Ingebrigtsen, Kulmala, Thomsen	**Measuring the contribution of randomness, exposure, weather, and daylight to the variation in road accident counts**	**1995**	**Scandinavian countries**	**Coded**	
Bijleveld, Churchill	**The influence of weather conditions on road safety: an assessment of the effect of precipitation and temperature.**	**2009**	**Netherlands**	**Coded**	
Karlaftis, Yannis	**Weather Effects on Daily Traffic Accidents and Fatalities: Time Series Count Data Approach**	**2010**	**Greece**	**Coded**	
Brijs, Karlis, Wets	**Studying the effect of weather conditions on daily crash counts using a discrete time-series model**	**2008**	**Netherlands**	**Coded**	
Edwards	**The Relationship between Road Accident Severity and Recorded Weather**	**1998**	**UK**	**Coded**	
Herman, Brijs, Stiers, Offermans	The impact of weather conditions on road safety investigated on an hourly basis	2007	Netherlands	Not coded	Descriptive results
Qiu, Nixon	Effects of adverse weather on traffic crashes: Systematic review and meta-analysis	2008	Multiple	Not coded	Doubts about the quality of the meta-analysis.

3.1.2 Description of coded studies and sampling frames

Table 6 Characteristics of coded studies

Author(s)	Period covered	Country	Methodology / Design	Sample	Outcome variable	Road user type	Type of road	Weather variables	Other variables
Bergel, 2004	1975-1999	France	Time series – DRAG model. Monthly data	300 months	• Injury crashes • Fatalities	• All	• All • Secondary roads • Urban roads • Motorways • Main roads	• Rainfall (mm)	• Temperature • Frost days • Traffic (on motorways and main roads only)
Bergel, Rattaire, Aron, Doucet, Violette, 2010	1995-2005	France	Relative risk Risk ratio	/	• Injury crashes	• All	• All • Minor roads • Secondary roads • Motorways • Main roads	• Rain (exposed or not)	/
Bergel, Debbarh, Antoniou, Yannis, 2013	1975-2000 1987-2005 1985-2005	France, Netherlands, Greece	Time-series State space model. Monthly data	228 / 252 / 312 months	• Injury crashes	• All	• All • Rural roads • Motorways • Main roads	• Rainfall (mm)	• Temperature • Frost days • Traffic (on motorways and main roads only)
	1985-2005	Greece	Time-series Generalized linear models (GLM). Daily data	7669 days	• Injury crashes • Fatalities	• All	• All	• Rainfall (mm)	• Temperature
				251 months	• Injury crashes	• All	• All	• unusual high precipitation	• Temperature
Bijleveld, Churchill, 2009	1987-2006	Netherlands	Approximate likelihood model. Daily data	7304 days	• Fatalities plus hospitalized casualties	• All • Pedestrians • Cyclists • Light mopeds • Mopeds • Motorcyclists • Cars • LGV • HGV	• All	• Precipitation duration	
Brijs, Karlis, Wets, 2008	2001	Netherlands	Time-series Poisson Interger Autoregressive model (INAR) for count data. Daily data	365 days	• [Injury] crashes	• Cars	• All	• Precipitation duration • Intensity of rain	• Temperature • Sunshine • Exposure (vehicles counts)

Edwards, 1998	1980-1990	United Kingdom	Severity ratio Rain versus Fine weather	/	• Severity score	• All	• All	• Presence of rain (vs fine weather)	/
Elvik, Fridstrøm, Kaminska, Meyer, 2013	1991-2000 + 2002-2009	Norway	Cros-sectinoal – Negative regression model	11359 +13269 cities-days	• Injury crashes	• All	• All	• Rainfall (mm)	• Snow • Daylight • Weekdays/holidays • Traffic volume
Focant, Martensen, 2014	2003-2012	Belgium	Mean comparison. Daily data.	555 normal days vs 702 rainy days	• Injury crashes • Fatal crashes	• All • Pedestrian • Cyclist • Motorcyclist • Car • LGV • HGV	• All	• Presence of rain (vs fine weather)	/
Fridstrøm, Ingebrigtsen, 1991	1974-1986	Norway	Time-series - Probability models based on the negative binomial distribution. Monthly data	2808 counties-months	• [Injury] crashes • Injuries • Severity (ratio fatal acc/injury acc)	• All • Pedestrian + Cyclists • Car	• All	• Rainfall (mm)	• Exposure • Weather • Daylight • Road network • Crash reporting • vehicle inspection • Law enforcement • Drivers and vehicles • Alcohol
Fridstrøm, Ifver, Ingebrigtsen, Kulmala, Thomsen, 1995	1973-1987	Denmark, Finland, Norway, Sweden	Cross-sectional - Generalized Poisson regression models. Monthly data	1848 / 1716 / 3192 / 3456 counties-months	• Injury crashes • Fatal crashes • Fatalities	• All	• All	• Precipitation (mm) • Days with precipitation • Days with rainfall (mm)	• Exposure • Reporting and legislation • Weather • Daylight • Trend
Hermans, Wets, Van den Bossche, 2006 a	1991-2001	Belgium	Time-series State space model. Monthly data	108 months	• Crash risk (acc/vhcl) • Fatal risk (fatalities/acc)	• All	• Motorways	• Days of precipitation	• Snow • Temperature • Economic variables • Law • Population growth • Holidays
Hermans, Wets, Van den Bossche, 2006b	1974-1999	Belgium	Time-series State space model. Monthly data.	312 months	• Fatal or severe crashes • Minor injury crashes • Killed or seriously injured • Slightly injured	• All	• All	• Precipitation (mm) • Days with rain	• Sun • Frost • Thunderstorm • Laws and regulations
Yannis, Karlaftis, 2010	1985-2005	Greece	Time-series - Integer autoregressive model	7670 days	• [Injury] vehicles crashes • Vehicles fatalities	• Vehicle • Pedestrian	• All	• Precipitation (mm) • Precipitation lag 1	• Temperature • Days of the week

			(INAR). Daily data		• [Injury] pedestrians crashes • Pedestrian fatalities				• Month
Martensen, Focant, Diependaele, 2016	2003-2014	Belgium	Time-series State Space Model. Monthly data	132 months	• Injuries	• All • Pedestrian • Cyclist • Moped • Motorcyclist • Car	• All	• Precipitation (mm)	• Temperature • Frost days • Snow days • Sun • Wind

3.2 ANALYSIS OF THE STUDY RESULTS

3.2.1 Detailed overview of the results

Table 7 gives the main results of each coded study. The effects on road safety are coded as

↗ = significant increase of crash/victim numbers or of crash risk = threat to road safety

↘ = significant decrease of crash/victim numbers or of crash risk = improvement of road safety

- = no significant change

Table 7 Summary of study results

Author(s)	Country	Covered period	Dependant / outcome type	Effect on road safety	Exposure taken into account?	Main outcome - Description
Bergel, 2004	France	1975-1999	Injury crashes – All	↗	N	- Rainfall height was linked, positively, to the total number of injury crashes and fatalities
			Injury crashes – Secondary roads	↗	N	
			Injury crashes – Urban roads	↗	N	
			Injury crashes – Motorways	↗	Y	
			Injury crashes – Toll Motorways	↗	Y	
			Injury crashes – Main roads	↗	Y	
			Fatalities – All	↗	N	
			Fatalities – Secondary roads	↗	N	
			Fatalities – Urban roads	↗	N	
			Fatalities – Motorways	↗	Y	
			Fatalities – Toll Motorways	↗	Y	
			Fatalities – Main roads	↗	Y	
Bergel, Rattaire, Aron, Doucet, Violette, 2010	France	1995-2005	Injury crash risk – All	↗	Y	- The added risk appears high (2.4 in average in 2004). - In 2005, the added risk is the highest on main roads (2.64), second on secondary roads (2.41) and on motorways (2.38), third on minor roads (1.88). - The added risk is higher outside built-in areas (2.6) than the average value for the whole of France, and thus than inside built-in area (2)
			Injury crash risk – Motorways	↗	Y	
			Injury crash risk – Main roads	↗	Y	
			Injury crash risk – Secondary roads	↗	Y	
			Injury crash risk – Minor roads	↗	Y	
			Injury crash risk – Inside built-in area	↗	N	
			Injury crash risk – Outside built-in area	↗	N	
Bergel, Debbarh, Antoniou, Yannis, 2013	France, Netherlands, Greece (Athens)	1975-2000 1987-2005 1985-2005	Injury crashes – France – All	↗	N	- Rainfall is positively correlated with the number of injury crashes - On motorways, rainfall is positively correlated with the number of injury crashes both in France and the Netherlands - On the contrary, rainfall is negatively correlated with the number of injury crashes in the region of Athens, where the network mainly consists of urban roads
			Injury crashes – Netherlands – All	↗	N	
			Injury crashes – Athens – All	↘	N	
			Injury crashes – France – Motorways	↗	Both tested	
			Injury crashes – France – Main roads	↗	Both tested	
			Injury crashes – Netherlands – Motorways	↗	N	
			Injury crashes – Netherlands – Rural roads	↗	N	
	Greece (Athens)	1985-2005	Injury crashes	↘	N	- Negative correlation between precipitation and the number of injury crashes. - The magnitude of the effects increases in the case of higher values - Non-significant effect on fatalities
			Fatalities	-	N	
Bijleveld, Churchill, 2009	Netherlands	1987-2006	Fatalities plus hospitalized casualties - All	↘	N	- The effect is different for different levels of crash severity and this effect is different for vulnerable transport modes and less vulnerable transport modes. - The number of fatalities appears to be less sensitive to the duration of precipitation than the number of in-patients, which in turn is less sensitive to the duration of
			Fatalities plus hospitalized casualties - Pedestrians	↗	N	
			Fatalities plus hospitalized casualties - Cyclists	↗	N	
			Fatalities plus hospitalized casualties – Light mopeds	↗	N	

			Fatalities plus hospitalized casualties - Mopeds	↗	N	precipitation than the number of slightly injured. - Coefficients among vulnerable modes of transport are relatively low, and some are even negative
			Fatalities plus hospitalized casualties - Motorcyclists	↗	N	
			Fatalities plus hospitalized casualties - Cars	↘	N	
			Fatalities plus hospitalized casualties - LGV	↘	N	
			Fatalities plus hospitalized casualties - HGV	↘	N	
Brijs, Karlis, Wets, 2008	Netherlands	2001	Cars injury crashes	↗	Y	- Intensity of rain and precipitation duration are highly significant: the intensity/duration of the rain increases, then this leads to a higher number of crashes
Edwards, 1998	United Kingdom	1980-1990	Severity	↘	N	- Crash severity decreases significantly in rain compared with fine weather
Elvik, Fridstrøm, Kaminska, Meyer, 2013	Norway	1991-2000 2002-2009	Injury crashes	↗	Y	- Amount of rainfall is highly significant, and induces an increase of injury crashes
Focant, Martensen, 2014	Belgium	2003-2012	Injury crashes – All	-	N	- The influence of rain on the number of crashes depends on the crash severity and the road user type. - For rainy days, no difference to the overall number of crashes on normal days was found. But rain is associated with an increase of injury crashes involving motorized 4-wheel vehicles, and a decrease of injury crashes involving a two-wheeler. - Fatal crashes are less frequent on rainy day. It's mainly the case for fatal crashes involving a two-wheeler or a HGV.
			Injury crashes – Pedestrian	-	N	
			Injury crashes – Cyclist	↘	N	
			Injury crashes – Motorcyclist	↘	N	
			Injury crashes – Car	↗	N	
			Injury crashes – LGV	↗	N	
			Injury crashes – HGV	↗	N	
			Fatal crashes – All	↘	N	
			Fatal crashes – Pedestrian	-	N	
			Fatal crashes – Cyclist	↘	N	
			Fatal crashes – Motorcyclist	↘	N	
			Fatal crashes – Car	-	N	
			Fatal crashes – LGV	-	N	
			Fatal crashes – HGV	↘	N	
Fridstrøm, Ingebrigtsen, 1991	Norway	1974-1986	Injury crashes – All	↗	Y	- The expected number of casualties appears to increase significantly with the amount of rainfall
			Fatal crashes – All	↗	Y	
			Injuries – All	↗	Y	
			Fatalities – All	↗	Y	
			Injuries – Car	↗	Y	
			Injuries – Cyclist and pedestrian	↗	Y	
			Severity	-	Y	
Fridstrøm, Ifver, Ingebrigtsen, Kulmala, Thomsen, 1995	Denmark, Finland, Norway, Sweden	1973-1987	Injury crashes DK	↗	Y	- Rainfall is liable to increase the crash toll [except in Norway for fatal outcomes]
			Injury crashes FI	↗	Y	
			Injury crashes NO	↗	Y	
			Injury crashes SE	↗	Y	
			Fatal crashes DK	↗	Y	
			Fatal crashes NO	↘	Y	
			Fatal crashes SE	↗	Y	
			Fatalities FI	↗	Y	
			Fatalities NO	↘	Y	
			Fatalities SE	↗	Y	
Hermans, Wets, Van den Bossche, 2006a	Belgium	1991-2001	Crash risk (acc/vhcl)	↗	Y	- The monthly number of days with precipitation increases the risk to have an crash but lowers the riks of fatalities in the crashes that occurr.
			Fatal risk (fatalities/acc)	↘	N	
Hermans, Wets, Van den Bossche, 2006b	Belgium	1974-199	Fatal or severe crashes	-	N	- Precipitation (amount and days) is a factor that causes more crashes and casualties - The quantity of precipitation is only relevant for the number of crashes with lightly injured persons and the number of persons lightly inured.
			Minor injury crashes	↗	N	
			Killed or seriously injured	↗	N	
			Slightly injured	↗	N	
Yannis, Karlaftis, 2010	Greece (Athens)	1985-2005	[Injury] Vehicles crashes	↘	N	- An increase in mean daily precipitation height or in its lagged value is significantly associated with a reduction of all types of incidents.
			Vehicles fatalities	↘	N	
			[Injury] Pedestrians crashes	↘	N	
			Pedestrian fatalities	↘	N	

Martensen, Focant, Diependaele, 2016	Belgium	2003-2014	Injuries – All	-	N	- Rain has a differential effect on victims among the two-wheelers and among car occupants. While the number of two-wheeler victims decrease in rainy weather, they increase among the car occupants. As a consequence of these opposite tendencies, there is not overall effect of rain on all road users jointly.
			Injuries – Pedestrian	-	N	
			Injuries – Cyclist	↘	N	
			Injuries – Moped	-	N	
			Injuries – Motorcyclist	↘	N	
			Injuries – Car	↗	N	

3.2.2 Difference of rain effects by outcome severity

While the pattern of results presented in Table 2 seems to suggest that rain affects less severe crashes more strongly than fatal ones, this could also be an artefact of the sample size for each type of study. Fatal crashes are generally fewer than injury crashes, making effects more likely to become significant when tested on injury crashes.

As noted above, only three studies have tested directly whether crash severity is affected by rain. Two of these (Hermans et al., 2006a; Edwards, 1998) found that crashes in rainy conditions are significantly less serious than in fine weather. The third study (Fridstrom et al., 1991) found a non-significant result, which in tendency pointed in the other direction (more severe crashes in rainy conditions).

As three studies are relatively few, we also compared the effect on the less severe outcome (e.g., injury crashes) to that on the more severe outcome (e.g. fatal crashes) for all studies where these two had been estimated in a comparable way.

Table 8 Studies showing a different impact of rain depending on outcome severity

		Increase in crashes/ victims in at least one category	
		Injury effect > Fatal effect	Fatal/ksi effect > Injury effect
Bergel, 2004	All (fatal acc vs. injury acc)	x	
	Secondary roads (fatal acc vs. injury acc)		x
	Urban roads (fatal acc vs. injury acc)	x	
	Motorways (fatal acc vs. injury acc)	x	
	Toll Motorways (fatal acc vs. injury acc)	x	
	Main roads (fatal acc vs. injury acc)		x
Hermans, Wets, Van den Bossche, 2006b	Crashes (ksi vs. li)	x	
	Victims (ksi vs. li)	x	
Fridstrøm, Ifver, Ingebrigtsen, Kulmala, Thomsen, 1995	DK (fatal vs. injury crashes)		x
	NO (fatal vs. injury crashes)	x	
	SE (fatal vs. injury crashes)		x
Fridstrøm, Ingebrigtsen, 1991	Crashes (fatal vs injury)		x
	Victims (fatal vs. injury)		x

The 15 comparisons that could be made were almost equally distributed between the expected larger effect for injury crashes (8) and the contrary result, a larger effect for fatal crashes (7).

To conclude, the direct evidence for a greater impact of rain on less severe crashes is not very strong. It should be noted, however, that almost all results against this hypothesis came from two Scandinavian studies (Fridstrom et al., 1991; 1995).

3.3 FULL LIST OF CODED STUDIES

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Bijleveld, F., & Churchill, T. (2009). *The influence of weather conditions on road safety. An assessment of the effect of precipitation and temperature*. Leidschendam (The Netherlands): Swov Institute for Road Safety Research.

Brijs, T., Karlis, D., & Wets, G. (2008). Studying the Effect of Weather Conditions on Daily Crash Counts Using a Discrete Time Series Model. *Accident Analysis and Prevention*, 40(3), pp. 1180-1190.

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Martensen, H., Focant, N., & Diependaele, K. (2016). Let's talk about the weather. Interpretation of short term changes in road accident outcomes. *Proceedings of 6th Transport Research Arena, April 18-21, 2016, Warsaw, Poland*.

Yannis, G., & Karlaftis, M. G. (2010). Weather Effects on Daily Traffic Accidents and Fatalities: A Time Series Count Data Approach. *TRB 89th Annual Meeting Compendium of Papers DVD*.

3.4 EXTRA REFERENCES

Aron, M., Bergel-Hayat, R., Saint-Pierre, M., & Violette, E. (2007). *Added risk by rainy weather on the roads of Normandie-Centre region in France. Some elements for the French IRCAD-SARI traffic monitoring and information system for drivers and operators.*

Elvik, R. (2016). Does the influence of risk factors on accident occurrence change over time? *Accident Analysis and Prevention, 91*, pp. 91-102.

Elvik, R., & Kaminska, J. (2011). *Effects on accidents of reduced use of studded tyres in Norwegian cities.* Oslo: TOI Transportøkonomisk institutt Norwegian Center for Transport Research.

Fridstrøm, L. (2000). *Piggfrie dekk i de største byene.* Oslo: TOI Transportøkonomisk institutt Norwegian Center for Transport Research.

Hermans, E., Brijs, T., Stiers, T., & Offermas, C. (2006). The Impact of Weather Conditions on Road Safety Investigated on an Hourly Basis. *Proceedings of the 85th Annual Meeting of the Transportation Research Board.*

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Synopsis 9:

Adverse weather conditions – Frost & Snow

1 Summary

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COLOUR CODE: GREY - UNCLEAR

Frost and snow are more often found to reduce crashes than to increase them. However, fost and snow also lead to a reduction in traffic participation – in particular for unprotected road users like cyclists, pedestrians and motorcyclists. So far, these mobility effects have been insufficiently accounted for, leaving the true risk unknown.

1.1 ABSTRACT

The effects of snow and frost on crash occurrence and risk have been found to be very inconsistent. For **frost**, *if* results are significant, they indicate a reduced crash occurrence (i.e. an improvement of road safety). Only on motorways frost tends to lead to an increased crash risk. For **snow** the results are more inconsistent with somewhat more positive effects (i.e. reduction of crashes) than negative effects (increased crash numbers). The first snow after a time of no snow seems to be consistently associated with a higher crash risk.

The risks associated with frost and snow are slippery roads and for snow also reduced visibility. These risks might be offset by more careful road user behaviour. However, much more likely the actual crash risk is influenced by a reduction of mobility (traffic volume) – in particular for unprotected road users like pedestrians, cyclists, and motorcyclists. So far, these mobility effects have been insufficiently accounted for, leaving the true risk unknown.

1.2 BACKGROUND

1.2.1 What is the effect of snow and frost on road safety?

When looking at the effect of a weather condition, it is important to differentiate between the crash *risk* that is associated with rainfall and the *net-effect* on the number of crashes.
In terms of **risk of crash**, frost and snow are associated with a reduced grip (ice-forming) and snow also with a reduced visibility. Studies indicate that road users seem to adjust their behaviour (reduced speed, less frequent overtaking, etc.) in particular for snow.
Wintery weather like frost and snow also affects the **exposition to this risk**, i.e. the mobility and its characteristics. When a substantial amount of snow has fallen, all road users avoid unneccessary trips, while frost and small amounts of snow are thought to affect mostly the mobility of two-wheelers and pedestrians, who are much more susceptible to weather conditions than car occupants.

1.2.2 What is the effect of snow and frost on crash type?

SafetyCube crash scenario reveals that the percentage of single vehicle crashes is much higher under snowy conditions than under dry ones, as well as driving crashes ingeneral (i.e. crashes that are initiated by a driving error (initially) without the interference of an opponent) and crashes in bends. On the opposite, the share of crashes at junction is much smaller under snowy weather.

1.2.3 How is the effect of snow and frost studied?

The present overview focusses on recent (from 1990 to current) studies in European studies. The majority of the studies have employed a multivariate model, in particular time-series models. The variation of the number of crashes over time is explained by different possible factors, such as calendar variables, interventions like new road safety laws and a large variation of weather variables. Snow and frost are often included in the model as one of these possible explanatory variables, and this under one or another form: snow-depth, days with snow, days with frost, amount of snow fallen, etc.

The effects of snow and frost on mobility can offset possible crash risks that are associated with these two factors. As a consequence the net-effect is often a reduction of crashes, because there are simply fewer people on the road. In order to study the crash ***risk*** (the chance for someone who is actually traveling to have an crash), it is necessary to correct for the change in traffic volume. Many studies include the traffic volume, in particular ***motorvehicle*** volume. However, a reduced mobility of pedestrians and cyclists might be much more important for the observed reduction of crashes. The true risk associated with frost and snow must therefore be considered unclear.

1.3 OVERVIEW OF RESULTS

1.3.1 Main results

10 key studies establishing the net-effect and the risk associated with frost and snow in European countries have been examined and a vote-count analysis has been conducted. A total number of 83 effects of snow and 53 effects of frost are reported in the selected studies. Among these, respectively 57 and 31 study the (global) impact on the total number of crashes or victims (regardless of the type of user, type of route, etc.). The results of these studies are reported in the following table.

Table 1 Percentage of significant positive effects

	Total number of effects tested	Result (% of effects)	
		Significant positve effects on Road Safety (e.g. reduced crash frequency)	Significant negative effects on Road safety (e.g. increased crash frequency)
Frost	31	55%	0%
Snow	57	39%	23%

Here are the main conclusions:

- The effect of frost on road safety – if there is an effect – is a positive one: fewer crashes under frost conditions.
- Only on motorways, frost tends to increase the crash risk.
- The effect of snow is mixed, but more often positive (i.e. fewer crashes) than negative.
- The first snow is associated with a higher crash risk than any subsequent snow.
- The results are thought to be due to a reduction in (vulnerable) road user mobility, which is insufficiently accouted for in the studies summarized.
- There is no evidence for different impacts on fatal crashes as opposed to less severe ones.

1.3.2 Transferability

The synopsis focuses on Europe, where studies exist mainly for north-western countries. The effects are inconsistent, with no clear pattern. Many variables are likely to play a role, like the frequency of frost and snow (which might influence compensatory behaviour), the modal share of weather-sensitive modes like cycling and walking, winter maintenance, vehicle equipment. Therefore the transferability of results from one country to another is relatively low, especially if countries have a different climate or share of road users.

2 Scientific overview

2.1 LITERATURE REVIEW

2.1.1 What is the effect of snow and frost on road safety?

When looking at the effect of snow and frost, it is important to differentiate between the crash *risk* that is associated with these weather conditions and the *net-effect* on the number of crashes.

In terms of **risk of crash**, snow undermines two crucial elements for security: grip and visibility. Snow and frost (when combined with wet roads) can lead to ice forming on the road, which dangerously reduces the friction of the road surface. This can lead to skidding and loss of control over the vehicle. Falling snow also causes a reduced visibility, especially when it is intense.

If a road surface has an open structure, such as porous asphalt, wet parts of the road surface will freeze quicker than surfaces with a closed structure. When there is black ice, a thin layer of ice forms so quickly on porous asphalt that the asphalt loses its friction. Roads that have just been laid also have a greater risk of slipperiness: the layer of black bitumen has a lower temperature and is thus more sensitive to wet parts freezing. (SWOV, 2012).

On the positive side, road users seem to be more careful when there is snow and ice. They drive more slowly and pay more attention than in normal weather (Sabir, 2011). Moreover, snow – especially when there is lots of it – can increase safety by forming soft barriers at the side of the road.

Snow does however, not only affect the risk to have an crash, but also the **exposition to this risk**, i.e. the mobility and its characteristics. Many road users avoid all (unnecessary) trips when there is snow (Eisenberg & Warner, 2005; Fridstrøm & al., 1995; Bos, 2001; Cools & al., 2010b). This concerns vulnerable road users but also motorized traffic (Cools & al., 2010a). For frost (in the absence of snow), it can be assumed that ***vulnerable road users who are much more exposed to the cold*** air will reduce their trips, while traffic in motorvehicles (except motorcycles) should remain more or less the same.

The changes to the traffic volume can be so strong, that even with an increase in risk the observed number of crashes can be reduced by snow and frost.

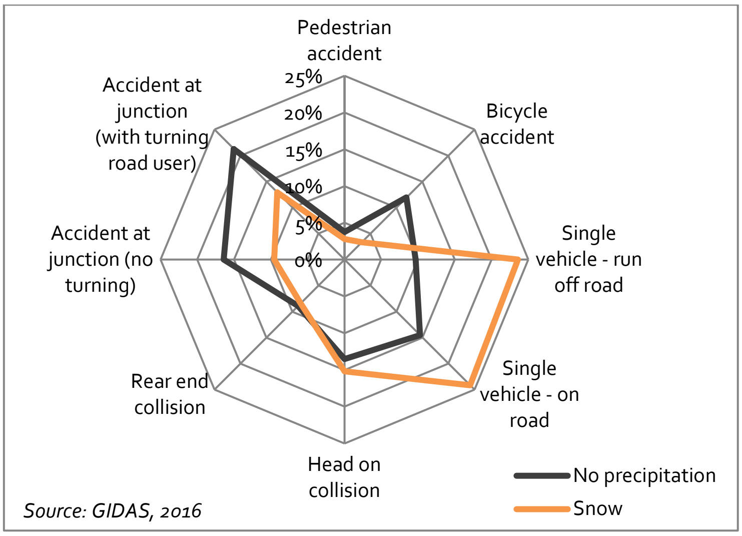
The severity of crashes has consistently been found to be reduced with snow, as minor crashes (damage only and slight injuries) have been observed to increase while the number of severe crashes is reduced (Fridstrøm & al., 1995; Eisenberg & Warner, 2005; Bos, 2001; Strong & al., 2010; Andrey, 2003; Sabir2011; SWOV, 2012). This is generally attributed to the reduced speed under snow-conditions.

2.1.2 Crash scenarios

SafetyCube crash scenarios allow to compare crashes in snowy conditions to those in dry/clear conditions (Figure 1).

This crash scenario analysis was conducted using cases from the German In-Depth Accident Study (GIDAS) database. All crashes were considered which were ready for analysis and which were collected in the years 2007 to 2015. In total, records from 14.398 crashes which occurred in the regions of Hannover and Dresden were analysed. The GIDAS database details those crashes which occurred on a public road where at least one person was injured. The crashes are collected according to a statistical sampling process to ensure a high level of representativeness of the actual crash situation in the sample regions. The data collection is conducted using the "on the scene" approach where all factors which were present at a crash are recorded. This does not mean that the recorded factor was a contributory factor towards the crash. For the current analysis all crashes where snow was listed as present at the crash scene were compared to all crashes where no type of precipitation was present at the crash scene.

Figure 1 Share of the different crash types under rain and "no precipitation" weather



Under snowy conditions the percentage of single vehicle crashes is much higher than under dry ones, as well single crashes on road as the ones with a vehicle running off the road. When it snows, almost 25% of the analysed German crashes are single vehicle crashes. This is probably the consequence of an increase number of losses of vehicle control, due to the reduced grip on the road. This is confirmed by the increased share of driving crashes (i.e. crashes that are initiated by a driving error (initially) without the interference of an opponent) and of crashes in bends observed in the GIDAS data when it's snowing (not shown here).

On the opposite, the share of crashes at junction is much smaller under snowy weather, what could reflect the greater caution of drivers at these risky locations. As under rainy conditions, crashes with bicyle are less frequent under snow, what could be explained by a reduced traffic of two-wheelers in such conditions.

2.2 DESCRIPTION OF STUDIES

2.2.1 How is the effect of snow and frost studied?

For the present overview the focus is on recent (from 1990 to current) European studies and the majority of the studies have employed a multivariate model, in particular time-series models. The variation of the number of crashes over time is explained by different possible factors, such as calendar variables, interventions like new road safety laws and a large variation of weather variables. Snow and frost are often included in the model as one of these possible explanatory variables, and this under one or another form: snow-depth, days with snow, days with frost, amount of snow fallen, etc.

Given the strong effect of snow and frost on mobility, it is essential whether the *traffic volume* is included into the analysis model. If the traffic volume is included (or some proxy for it, e.g. oil sales, number of toll-tickets) then the results measure the effect of snow on the *crash risk*. If it is not included, then the results measure the *net-effect* on the number of crashes or injuries. It must be noted, however, that so-far no study has included a measure for the mobility for vulnerable road users, which means that even if the a crash risk is estimated for motorized vehicles, the observed effects for unprotected road users are still net-effects.

In three studies, the dependent variable was crash severity.

2.2.2 Transferability

The size of the effects are difficult to compare across studies, because the effects are mostly expressed as a coefficient in a multivariate model, which vary a lot with respect to model-architecture and other variables included. Many variables are likely to play a role for the total effect. For example:

- the frequency and amount of snow-fall (might influence compensatory behaviour)
- the modal share of weather-sensitive modes like cycling and walking
- snow removal, the use of salt, the use of snow chains & winter-tires, ...
- the quality of the road-surface

In this sense, the transferability of results from one country to another is relatively low, especially if countries have a different climate.

2.3 DESCRIPTION OF ANALYSIS CARRIED OUT

2.3.1 Vote-count analysis

10 key studies establishing the risk or the net effect of snow and frost in European countries have been coded, analysed and summarized. While most studies used multivariate methods to estimate the effect of snow/frost, the model architecture and included variables differ too much between studies to allow a meta-analysis of the results. Instead a vote-count analysis has been conducted: each test that is executed in one of the studies (or more specifically each coefficient) has one vote on the effect of snow/frost. The results are coefficients and a positive coefficient indicates an increase of the dependent variable when it snows/freezes and a negative coefficient a decrease. Of course the coefficient can also be non-significant (which means usually that it has been excluded from the final model). Consequently, the vote can take three different values:

- \- Negative effect (i.e. positive correlation or increase of acc/inj/risk)
- \+ Positive effect (i.e. negative correlation or decrease of acc/inj/risk.
- / No significant effect

These vote-counts are analysed with respect to different characteristics of the dependent variables: net-effect versus impact on risk, outcome severity, road user type, type of road, etc. Whether the analyses are based on victim counts or crash counts seems to make very little difference. This variable is therefore not taken up in the following analyses, which are aggregated over effects found on victim numbers and effects found on crash numbers.

A total number of 83 effects of snow and 53 effects of frost are reported in the selected studies.

2.3.2 Crash-risk and crash occurrence

The table below shows the impact of snow and frost on the total number of crashes/victims and on the global crash/injury risk (regardless of the type of user, type of route, etc.). Specific effects for sub-categories of road user or road type are presented in subsequent tables.

Table 1 Vote-count analysis for effects of frost and snow on crash risk or crash occurrence

	Total number of effects tested	Result (number of effects)			Result (% of effects)	
		-	/	+	+	-
Frost	**31**		**14**	**17**	**55%**	**0%**
Crash occurrence	9		1	8	89%	0%
Risk	22		13	9	41%	0%
Snow	**57**	**13**	**22**	**22**	**39%**	**23%**
Crash occurrence	8		5	3	38%	0%
Risk	49	13	17	19	39%	27%

Note: - Negative effect (i.e. positive correlation or increase of acc/inj/risk); + Positive effect (i.e. decrease of acc/inj/risk); / no significant effect

For frost, no negative effects on road safety have been found. In contrast to expectation, purely in terms of crash occurrence, frost consistently shows a benign effect (i.e. fewer crashes and victims in 89% of the studies). However, in those studies where the traffic volume has been taken into account, the positive effect often disappears – suggesting that the reduction of crashes is due to reduced mobility rather than a reduction in risk.

For snow, there is never a negative ***net-effect*** (i.e. number of crashes actually observed is – if at all affected – reduced), but for the crash ***risk*** increases and decreases have been found in approximately equal shares.

A word of caution is necessary concerning the interpretation of the "risk" effects. These result from studies in which changes to the traffic volume have been taken into account and should therefore reflect the crash risk (given that one is taking part in traffic). However, the mobility is usually measured in terms of motorvehicle traffic volume and the mobility of pedestrians, cyclists, or even motorcyclists can be quite different from that, which means that changes in the travelbehaviour of those road users that are most exposed to the weather conditions have still not been taken into account.

As an example, a reduction of crash *risk* due to *frost* is very difficult to understand. If anything, the risk should be increased due to the higher danger of ice-forming on the road. While the motorvehicle traffic volume is accounted for, it is quite likely that the reduction of crash risk is due to a reduced mobility of unprotected road users. ***This means that the correction by motorvehicle traffic volume seems insufficient to isolate the actual risk***. The differentiation between crash occurrence and risk is therefore left out in the following tables.

2.3.3 Crash-risk by type of snow measurement

While for frost mostly the number of days with frost has been used to predict crash numbers, for snow there have been mainly three different variables that have been tested: the amount of snow (e.g. snow-depth, amount of snow fallen), number of days with snow, and the first occurrence of snow.

Table 2 Vote-count analysis for effects of snow on crash -risk by type of snow measurement

	Total number of effects tested	Result (number of effects)			Result (% of effects)	
		-	/	+	+	-
Snow	**49**	**13**	**17**	**19**	**39%**	**27%**
Amount of snow	18	1	7	10	56%	6%
Days with snow	15	2	5	8	53%	13%
First snow	15	10	4	1	7%	67%
Other	1		1		0%	0%

Note: - Negative effect (i.e. positive correlation or increase of acc/inj/risk); + Positive effect (i.e. decrease of acc/inj/risk); / no significant effect

Interestingly, the only variable that consistently indicates an increased risk is "first snow".

2.3.4 Crash-risk by severity

Table 3 Vote-count analysis for effects of frost and snow on crash -risk by by severity

	Total number of effects tested	Result (number of effects)			Result (% of effects)	
		-	/	+	+	-
Frost	**22**		**13**	**9**	**41%**	**0%**
Fatal	12		7	5	42%	0%
Injury	10		6	4	40%	0%
Snow	**49**	**13**	**17**	**19**	**39%**	**27%**
Fatal	24	6	9	9	38%	25%
Injury	25	7	8	10	40%	28%

Note: - Negative effect (i.e. positive correlation or increase of acc/inj/risk); + Positive effect (i.e. decrease of acc/inj/risk); / no significant effect

In Table 3 it can be seen that the results of snow- and frost-effects are very similar for fatal crashes and injury crashes. This is in contradiction to older research results – in particular outside of Europe. An explanation might concern the role of vulnerable road users (which are likely to play a much larger role in Europe than in the United States, for instance), because in general this group has a higher share among injury crashes as compared to fatal crashes (OECD/ITF 2011). Possibly a smaller share of crashes with pedestrians and cyclists, affects injury crashes more than fatal ones – which could offset stronger reduction of fatal crashes that could have been found otherwise.

One article also studies the impact of snow on crash severity. Whatever the snow measurement (presence of snow, snow amount or first snow), the result is not significant.

2.3.5 Crash-risk and crash occurrence by road user and road type

There are too few studies that have split up the effects of snow and frost by road-user type to make a vote count analysis possible. The few studies conducted show however big differences with much stronger effects of snow on the crash occurrence of motorcyclists, pedestrian, and cyclists, as compared to car occupants (Focant & Martensen, 2014, Martensen, et al., 2016).

The results per road-type are given in Table 4. Studies of crash-occurrence and crash risk are analysed jointly. For snow-effects, no studies were found that differentiate different road types.

Table 2 Vote-count analysis for effects of frost and snow on crash-occurrence and risk by road type

	Total number of effects tested	Result (number of effects)			Result (% of effects)	
		-	/	+	+	-
Frost	**47**	**6**	**19**	**22**	**47%**	**13%**
All	31		14	17	55%	0%
Motorway	7	5	2		0%	71%
Rural	7	1	3	3	43%	14%
Urban	2			2	100%	0%
Snow	**57**	**13**	**22**	**22**	**39%**	**23%**
All	57	13	22	22	39%	23%

Note: - Negative effect (i.e. positive correlation or increase of acc/inj/risk); + Positive effect (i.e. decrease of acc/inj/risk); / no significant effect

Studies that consider all road types together typically find fewer crashes when it is freezing – or no significant result at all. Although few studies split up the frost effect by road-type, there is one relatively consistent result: on motorways, the effect of frost is never a good one and mostly a bad one (more crashes/ higher risk). It is interesting that this is the one place where the mobility of pedestrians and cyclists cannot have an effect. This could again point to the possibility that the positive frost effects on other road types might actually be due to a reduced mobility of that group in cold weather.

2.4 CONCLUSION

The effects of snow and frost on crash occurrence and risk have been found to be very inconsistent. For frost, no increased risk has been found and if results are significant, they indicate a reduced crash occurrence (i.e. an improvement of road safety). For snow the results are very inconsistent with somewhat more positive effects (i.e. reduction of crashes) than negative effects (increased crash numbers). The first snow after a time of no snow seems to consistently increase the crash risk though.

The risks associated with these two factors are thought to be offset by a reduction of mobility – in particular of unprotected road users like pedestrians, cyclists, and motorcyclists. This mobility effect has been insufficiently accounted for in risk models – even those that took into account the motorvehicle traffic volume.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature search strategy

Principles

As researches studying the impact of adverse weather on road safety are usually not limited to one meteorological factor, the literature search was conducted together for the three conditions of adverse weather selected for the SafetyCube project (rain, snow/frost and wind).

Excluded:

- effect of climate change
- impact on crashes in tunnels
- impact on mobility, traffic/transport/flow, driver's behaviour (speed, etc.), vehicle's behaviour (deviation, etc.)
- evaluation of countermeasures (wind fences, tires, road maintenance, education, weather information systems, speed limit, asphalt composition, etc.)
- effect of road surface conditions
- studies that answer to the question "in which conditions is the rain/snow/wind the more risky?"

Research searchterms and hits

Database: Scopus **Date:** 7th and 8th of April 2016

Limitations/ Exclusions:

- Search field: TITLE-ABS-KEY
- Published: 1990 to current
- Document Type: ALL
- Subject Area: ALL

	search no.	search terms / operators / combined queries	hits
snow	#1	(TITLE-ABS-KEY (snow OR ice OR temperature OR hail OR frost) AND TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities"))	620
	#2	(TITLE-ABS-KEY (snowfall) AND TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities")	23
wind	#1	KEY (wind) AND KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident")	40
	#2	KEY (wind) AND KEY ("accident risk" OR "crash risk")	20
	#3	(TITLE-ABS-KEY (wind) AND TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk"))	149
rain	#1	TITLE-ABS-KEY (rain OR precipitation) AND TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk")	186
	#2	TITLE-ABS-KEY (rainfall) AND TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk")	64

Database: TRID **Date:** 7th and 8th of April 2016

Limitations/ Exclusions:

- Published: 1990 to 2016
- Document source : ALL, Document Type: ALL, Subject area : ALL
- Language: English and French

	search no.	search terms / operators / combined queries	hits
snow	#1	Snow "road safety"+ snow "road accident" + snow "accident risk"	387 + 42 + 37
	#2	ice "road safety"+ ice "road accident" + ice "accident risk"	296 + 36 + 24
	#3	temperature "road safety"+ temperature "road accident" + temperature "accident risk"	222 +24 + 12
	#4	hail frost "road safety" "+ hail frost "road accident" + hail frost "accident risk"	52
	#5	Neige/glace/gel/verglas/température/grêle "sécurité routière »	36
wind	#1	wind, "road safety"	123
	#2	wind "road accident"	8
	#3	wind "accident risk"	16
	#4	Vent "sécurité routière"	15
rain	#1	rain "road safety" / precipitation "road safety"	153 + 81
	#2	rain "road accident" / precipitation "road accident"	19 + 18
	#3	rain "accident risk" / precipitation "accident risk"	30 + 24
	#4	Pluie "sécurité routière"/ précipitations "sécurité routière"	26 + 5

Database: ScienceDirect **Date:** 7th and 8th of April 2016

Limitations/ Exclusions:

- Search field: Abstract, title, keywords
- Published: 1990 to current
- Document Type: ALL
- Subject Area: ALL

	search no.	search terms / operators / combined queries	hits
snow	#1	TITLE-ABSTR-KEY(snow OR ice OR temperature OR hail OR frost OR snowfall) and TITLE-ABSTR-KEY("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities").	49
wind	#1	TITLE-ABSTR-KEY(wind) and TITLE-ABSTR-KEY("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk").	127
rain	#1	TITLE-ABSTR-KEY(rain OR precipitation) and TITLE-ABSTR-KEY("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk")	34
	#2	TITLE-ABSTR-KEY(rainfall) and TITLE-ABSTR-KEY("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk").	19

Database: Google Scholar **Date:** 7th and 8th of April 2016

Limitations/ Exclusions:

- Published: 1990 to current
- Document Type: ALL
- Sorted by relevance

	search no.	search terms / operators / combined queries	hits
snow	#1	snow "road safety"	7300 first 5 results pages only
	#2	Snowfall "road safety"	17500 first 5 results pages only
	#3	Frost ice "road safety"	827 first 5 results pages only
	#4	Temperature "road safety"	11900 first 5 results pages only
wind	#1	wind AND ("road accident" OR "road crash" OR "road fatalities" OR "road safety")	10200 first 5 results pages only
rain	#1	(rain OR rainfall OR precipitation) AND ("road accident" OR "road crash" OR "road fatalities" OR "road safety")	14800 first 10 results pages only
	#2	impact of rainfall on road crashes	17500 first 5 results pages only

Database: iRAP toolkit, iRAP website and CEDR website **Date:** 7th and 8th of April 2016

Nothing interesting

Results Literature Search

Database	Hits
Scopus (remaining papers after several limitations/exclusions)	1102
TRID	1686
ScienceDirect	229
Google Scholar	40 results pages
Total number of studies to screen title	**3017 + google**

Screening

Total number of studies to screen title (in order to evaluate the relevance to the topic)	3017 + google
Number of articles remaining after screening of the title **= Total number of studies to screen abstract**	182
Remaining studies after abstract screening	110

Reference lists also screened:

Andrey J., Mills B., Leahy M., Suggett J.	*Weather as a chronic hazard for road transportation in Canadian cities*	*2003*
Karlaftis, Matthew G Yannis, George	*Weather Effects on Daily Traffic Accidents and Fatalities: Time Series Count Data Approach*	*2010*
KEITH K. KNAPP, LELAND D. SMITHSON, AND AEMAL J. KHATTAK	*Mobility and safety impacts of winter storm events in a freeway environment*	*2000*
Maze T.H., Agarwal M., Burchett G.	*Whether weather matters to traffic demand, traffic safety, and traffic operations and flow*	*2006*
Paul A. Pisano, Lynette C. Goodwin, Michael A. Rossetti	*US highway crashes in adverse road weather conditions*	*2004*
Qiu L., Nixon W.A.	*Effects of adverse weather on traffic crashes: Systematic review and meta-analysis*	*2008*
Strong C.K., Zhirui Y., Shi X.	*Safety effects of winter weather: The state of knowledge and remaining challenges*	*2010*
Swov factsheet	*The influence of weather on road safety*	*2009*
Theofilatos A., Yannis G.	*A review of the effect of traffic and weather characteristics on road safety*	*2014*

Total number of additional relevant articles identified in these reference lists: 12

Removed articles: 15

- 5, due to unspecified weather factors in the summary, and not found pdf
- 10, reviewing article (could be useful for summary)

Total number studies to screen full-text : 107

- **21 addressing "wind" (W) factor**
- **37 addressing "snow" (S) factor**
- **84 addressing "rain" (R) factor**

Prioritizing Coding

Prioritization:

1. Sorting of the papers according to their capability to answer the question "to what extent does this factor impact the number / frequency / severity of road crashes / victims?"
2. Priority to Meta-analyse
3. Among all "very high prior" papers, selection of studies from Europe

Following these prioritization criteria, the full-text screening of the 107 studies has allowed to select 10 papers to be coded.

3.1.2 Description of coded studies and sampling frames

Table 1 Characteristics of coded studies

Authors	Period covered	Country	Administrative level	Methodology / Design	Data frequency	Sample	Dependant	Severity	Road user type	Type of road	Urban/rural	Weather variables	Other variables
Bergel, Depire, 2004	1975-1999	France	National	Time series - DRAG Approach	Month	300 months	• Crash • Injury	• Injury crashes • Fatalities	• All	• All • Secondary roads • Urban roads • Motorways • Main roads	• All • Urban	• Frost days	• Temperature • Rainfall • Traffic (on motorways and main roads only)
Bergel, Debbarh, Antoniou, Yannis, 2013	1975-2000 1987-2005 1985-2005	France, Netherlands, Greece	National Local : Athens	Time-series State space locally linear trend and seasonal model	Month	228 / 252 / 312 months	• Crash	• Injury crashes	• All	• All • Rural roads • Motorways • Main roads	• All • Rural	• Frost days	• Temperature • Rainfall • Traffic (on motorways and main roads only)
Brijs, Karlis, Wets, 2008	2001	Netherlands	Local: 3 large cities	Time-series Poisson Integer Autoregressive model (INAR) for count data	Daily	365 days	• Crash	• [Injury] crashes	• Cars	• All	• Urban	• Temperature below 0°C	• Other temperature variables • Sunshine • Precipitation duration • Intensity of rain Exposure (vehicles counts)
Elvik, Fridstrøm, Kaminska, Meyer, 2013	1991-2000 + 2002-2009	Norway	Local: 4-5 large cities	Cros-sectinoal – Negative regression model	/	11359 +13269 cities-days	• Crash	• Injury crashes	• All	• All	• Urban	• Snowfall (mm) • Snow depth (cm) • Frost days • First snow • Last snow	• Rainfall • Daylight • Weekdays/holidays • Traffic volume
Focant, Martensen, 2014	2003-2012	Belgium	National	Mean comparison	Daily	555 normal days vs 702 rainy days	• Crash	• Injury crashes • Fatal crashes	• All • Pedestrian • Cyclist • Motorcyclist • Car • LGV • HGV	• All	• All	• Presence of snow (vs fine weather)	/

Fridstrøm, Ingebrigtsen, 1991	1974-1986	Norway	National	Time-series - Probability models based on the negative binomial distribution	Monthly	2808 counties-months	• Crash • Injury • Severity	• [Injury] crashes • Injuries • Severity (ratio fatal acc/injury acc)	• All • Pedestrian + Cyclists • Car	• All	• All	• Presence of snow • Snowfall (mm) • First snow	• Exposure • Weather • Daylight • Road network • Accident reporting • vehicle inspection • Law enforcement • Drivers and vehicles • Alcohol
Fridstrøm, Ifver, Ingebrigtsen, Kulmala, Thomsen, 1995	1973-1987	Denmark, Finland, Norway, Sweden	National	Cross-sectional - Generalized Poisson regression models	Monthly	1848 / 1716 / 3192 / 3456 counties-months	• Crash • Injury	• Injury crashes • Fatal crashes • Fatalities	• All	• All	• All	• Snow days • Snow depth (m) • Sudden snowfall • Frost (half-) days	• Exposure • Reporting and legislation • Weather • Daylight • Trend
Hermans, Wets, Van den Bossche, 2006 [Describing...]	1991-2001	Belgium	National	Time-series - unobserved components	Monthly	108 months	• Risk • Severity	• Crsh risk (crashes/vhcl) • Fatal risk (fatalities/acc)	• All	• Motorways	• All	• Snow days	• Precipitation • Temperature • Economic variables • Law • Population growth • Holidays
Hermans, Wets, Van den Bossche, 2006 [Frequency...]	1974-1999	Belgium	National	Time-series - unobserved components	Monthly	312 months	• Crash • Injury	• Fatal or severe crashes • Minor injury crashes • Killed or seriously injured • Slightly injured	• All	• All	• All	• Snow days • Frost days	• Sun • Precipitation • Frost • Thunderstorm • Laws and regulations
Martensen, Focant, Diependaele, 2016	2003-2014	Belgium	National	Time-series State Space Model	Monthly	132 months	• Injury	• Injuries	• All • Pedestrian • Cyclist • Moped • Motorcyclist • Car	• All	• All	• Snow days • Frost days	• Temperature • Precipitation (mm) • Sun • Wind

3.2 ANALYSIS OF THE STUDY RESULTS

3.2.1 Detailed overview of the results

Table 7 gives the main results of each coded study. The effects on road safety are coded as

- \- Negative effect (i.e. positive correlation or increase of acc/vict/risk)
- \+ Positive effect (i.e. negative correlation or decrease of acc/inj/risk)
- / No significant effect

Table 2 Summary of study results

Authors	Country	Measure	Dependant / outcome type	Effect on road safety	Corrected for Traffic volume?	Main outcome - Description
Bergel, Depire, 2004	France, 1975-1999	# Days of frost	Injury crashes – All	+	N	Occurrence of frost was linked, negatively, to the total number of injury crashes (decrease of number of crashes per additional days of frost). On the motorways network, this relation was inverse.
		# Days of frost	Injury crashes – Secondary roads	+	N	
		# Days of frost	Injury crashes – Urban roads	+	N	
		# Days of frost	Injury crashes – Motorways	-	Y	
		# Days of frost	Injury crashes – Toll Motorways	-	Y	
		# Days of frost	Injury crashes – Main roads	+	Y	
		# Days of frost	Fatalities – All	+	N	
		# Days of frost	Fatalities – Secondary roads	+	N	
		# Days of frost	Fatalities – Urban roads	+	N	
		# Days of frost	Fatalities – Motorways	-	Y	
		# Days of frost	Fatalities – Toll Motorways	-	Y	
		# Days of frost	Fatalities – Main roads	-	Y	
Bergel, Debbarh, Antoniou, Yannis, 2013	France, 1975-2000 Netherlands, 1987-2005 Greece (Athens), 1985-2005	# Days of frost	Injury crashes – France – All	+	N	[On all types of road] The occurrence of frost is negatively correlated with the number of injury crashes The occurrence of frost does appear to have a mixed effect according to the road type and the country.
		# Days of frost	Injury crashes – Netherlands – All	+	N	
		# Days of frost	Injury crashes – France – Motorways	/	N	
		# Days of frost	Injury crashes – France – Motorways	-	Y	
		# Days of frost	Injury crashes – France – Main roads	/	N	
		# Days of frost	Injury crashes – France – Main roads	/	Y	
		# Days of frost	Injury crashes – Netherlands – Motorways	/	N	
		# Days of frost	Injury crashes – Netherlands – Rural roads	/	N	
Brijs, Karlis, Wets, 2008	Netherlands, 2001	Mean temp<0	Cars injury crashes	-	Y	A mean temperature below 0 is associated with an increase of the number of crashes (compared to a day with a mean temperature above 20)
Elvik, Fridstrøm, Kaminska, Meyer, 2013	Norway, 1991-2000 2002-2009	Snow fallen	1991-2000 – Injury crashes	/	Y	In both studies, most weather variables are not statistically significant Snowdepth and negative temperature are only significant in the first study (1991-2000, and are associated with a lower number of crashes.
		Snowdepth	1991-2000 – Injury crashes	+	Y	
		Mean temp <0	1991-2000 – Injury crashes	+	Y	
		Snow fallen	2002-2009 – Injury crashes	/	Y	
		Snowdepth	2002-2009 – Injury crashes	/	Y	
		Mean temp <0	2002-2009 – Injury crashes	/	Y	
		First snow	2002-2009 – Injury crashes	/	Y	
		Last snow	2002-2009 – Injury crashes	/	Y	
Focant, Martensen, 2014	Belgium, 2003-2012	Day with snow	Injury crashes – All	+	N	The influence of snow on the number of crashes depends on the crash severity and the road user type. Snow is associated with a decrease of the total number of injury and fatal crash, crashes involving a two-wheel and car crashes. The impact of snow is not significant in other cases.
		Day with snow	Injury crashes – Pedestrian	/	N	
		Day with snow	Injury crashes – Cyclist	+	N	
		Day with snow	Injury crashes – Motorcyclist	+	N	
		Day with snow	Injury crashes – Car	+	N	
		Day with snow	Injury crashes – LGV	/	N	
		Day with snow	Injury crashes – HGV	/	N	
		Day with snow	Fatal crashes – All	+	N	
		Day with snow	Fatal crashes – Pedestrian	/	N	
		Day with snow	Fatal crashes – Cyclist	/	N	
		Day with snow	Fatal crashes – Motorcyclist	+	N	
		Day with snow	Fatal crashes – Car	+	N	
		Day with snow	Fatal crashes – LGV	/	N	

		Day with snow	Fatal crashes – HGV	/	N	
Fridstrøm, Ingebrigtsen, 1991	Norway, 1974-1986	Day with snow	Injury crashes – All	+	Y	Generally speaking, snowfall appears to have a negative effect on traffic casualties in Norway (i.e. a favourable traffic safety effect). "Surprise effect" of the winter's first snowfall : increase of the six crash/injury dependent variables
		Day with snow	Fatal crashes – All	/	Y	
		Day with snow	Injuries – All	+	Y	
		Day with snow	Fatalities – All	/	Y	
		Day with snow	Injuries – Car	-	Y	
		Day with snow	Injuries – Cyclist and pedestrian	+	Y	
		Day with snow	Severity	/	Y	
		Snow fallen	Injury crashes – All	+	Y	
		Snow fallen	Fatal crashes – All	/	Y	
		Snow fallen	Injuries – All	+	Y	
		Snow fallen	Fatalities – All	/	Y	
		Snow fallen	Injuries – Car	/	Y	
		Snow fallen	Injuries – Cyclist and pedestrian	+	Y	
		Snow fallen	Severity	/	Y	
		First snow	Injury crashes – All	-	Y	
		First snow	Fatal crashes – All	-	Y	
		First snow	Injuries – All	-	Y	
		First snow	Fatalities – All	-	Y	
		First snow	Injuries – Car	-	Y	
		First snow	Injuries – Cyclist and pedestrian	-	Y	
		First snow	Severity	/	Y	
Fridstrøm, Ifver, Ingebrigtsen, Kulmala, Thomsen, 1995	Denmark, Finland, Norway, Sweden 1973-1987	# Days with snow	Denmark – Injury crashes	+	Y	Snowfall is liable to decrease the crash toll Even the incidence of frost comes out with a significantly negative coefficient. Here, however, the effect on fatal crashes/death victims appears to be smaller than on injury crashes in general.
		Sudden snowfall	Denmark – Injury crashes	-	Y	
		# Days of frost	Denmark – Injury crashes	/	Y	
		# Half-days of frost	Denmark – Injury crashes	+	Y	
		Snowdepth	Denmark – Injury crashes	/	Y	
		# Days with snow	Finland – Injury crashes	+	Y	
		Sudden snowfall	Finland – Injury crashes	-	Y	
		# Days of frost	Finland – Injury crashes	/	Y	
		# Half-days of frost	Finland – Injury crashes	/	Y	
		Snowdepth	Finland – Injury crashes	+	Y	
		# Days with snow	Norway – Injury crashes	+	Y	
		Sudden snowfall	Norway – Injury crashes	-	Y	
		# Days of frost	Norway – Injury crashes	+	Y	
		# Half-days of frost	Norway – Injury crashes	/	Y	
		Snowdepth	Norway – Injury crashes	-	Y	
		# Days with snow	Sweden – Injury crashes	/	Y	
		Sudden snowfall	Sweden – Injury crashes	/	Y	
		# Days of frost	Sweden – Injury crashes	+	Y	
		# Half-days of frost	Sweden – Injury crashes	/	Y	
		Snowdepth	Sweden – Injury crashes	+	Y	
		# Days with snow	Denmark – Fatal crashes	+	Y	
		Sudden snowfall	Denmark – Fatal crashes	-	Y	
		# Days of frost	Denmark – Fatal crashes	/	Y	
		# Half-days of frost	Denmark – Fatal crashes	+	Y	
		Snowdepth	Denmark – Fatal crashes	/	Y	
		# Days with snow	Norway – Fatal crashes	+	Y	
		Sudden snowfall	Norway – Fatal crashes	-	Y	
		# Days of frost	Norway – Fatal crashes	+	Y	
		# Half-days of frost	Norway – Fatal crashes	/	Y	
		Snowdepth	Norway – Fatal crashes	+	Y	
		# Days with snow	Sweden – Fatal crashes	/	Y	
		Sudden snowfall	Sweden – Fatal crashes	/	Y	
		# Days of frost	Sweden – Fatal crashes	+	Y	
		# Half-days of frost	Sweden – Fatal crashes	/	Y	
		Snowdepth	Sweden – Fatal crashes	+	Y	
		# Days with snow	Finland – Fatalities	-	Y	
		Sudden snowfall	Finland – Fatalities	+	Y	
		# Days of frost	Finland – Fatalities	/	Y	
		# Half-days of frost	Finland – Fatalities	/	Y	
		Snowdepth	Finland – Fatalities	+	Y	
		# Days with snow	Norway – Fatalities	+	Y	
		Sudden snowfall	Norway – Fatalities	-	Y	

		# Days of frost	Norway – Fatalities	+	Y	
		# Half-days of frost	Norway – Fatalities	/	Y	
		Snowdepth	Norway – Fatalities	+	Y	
		# Days with snow	Sweden – Fatalities	/	Y	
		Sudden snowfall	Sweden – Fatalities	/	Y	
		# Days of frost	Sweden – Fatalities	+	Y	
		# Half-days of frost	Sweden – Fatalities	/	Y	
		Snowdepth	Sweden – Fatalities	+	Y	
Hermans, Wets, Van den Bossche, 2006 [Describing…]	Belgium, 1991-2001	# Days with snow	Crash risk (crashes/vhcl)	-	Y	This study found a positive relationship between snow and crash risk.
		# Days with snow	Fatal risk (fataties/acc)	/	N	
Hermans, Wets, Van den Bossche, 2006 [Frequency…]	Belgium, 1974-199	# Days of frost	Fatal or severe crashes	+	N	The number of snow days is not found significant The only weather variable that has a positive effect on road safety in this study is the monthly percentage of days with frost.
		# Days of frost	Minor injury crashes	+	N	
		# Days of frost	Killed or seriously injured	+	N	
		# Days of frost	Slightly injured	+	N	
		# Days with snow	Fatal or severe crashes	/	N	
		# Days with snow	Minor injury crashes	/	N	
		# Days with snow	Killed or seriously injured	/	N	
		# Days with snow	Slightly injured	/	N	
Martensen, Focant, Diependaele, 2016	Belgium, 2003-2014	# Days with frost	Injuries – All	/	N	Snow also forms a very influential meteorological factor which turns out to be a protective one While snow leads to a reduction for all victim types, the effects are strongest for the motorized two-wheelers Frost almost never has a significant impact on the number of injuries
		# Days with frost	Injuries – Pedestrian	+	N	
		# Days with frost	Injuries – Cyclist	/	N	
		# Days with frost	Injuries – Moped	/	N	
		# Days with frost	Injuries – Motorcyclist	/	N	
		# Days with frost	Injuries – Car	/	N	
		# Days with snow	Injuries – All	+	N	
		# Days with snow	Injuries – Pedestrian	/	N	
		# Days with snow	Injuries – Cyclist	+	N	
		# Days with snow	Injuries – Moped	+	N	
		# Days with snow	Injuries – Motorcyclist	+	N	
		# Days with snow	Injuries – Car	+	N	

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Synopsis 10: Poor visibility – Darkness

1 Summary

Nathalie Focant, Heike Martensen (October 2016)

COLOUR CODE: YELLOW (PROBABLY RISKY)

Darkness has been consistently shown to be associated with an increase of crash risk for pedestrians. An overall incresase in risk has been found in most studies, however, this overall effect seems to be predominantly carried by an increased risk for pedestrians, and possibly for two-wheelers.Darkness is also associated with an increased severity of crash in the sense that severe and fatal crashes increase while crashes with minor injuries decrease in darkness.

1.1 ABSTRACT

When considering the total number of crashes, the absence of light is associated with an increased risk of crash. This effect is confirmed for pedestrians for wich the crash risk is systematically higher in darkness than in daylight. The crash risk for pedestrian is estimated to be 2 to 4 times higher in such conditions. The risk of crash in darkness also seems to increase for powered two-wheelers, but to a lesser extent (relative risk below 2). For cars, results do not show any significant impact of darkness. As fatalities and serious injuries are more likely in darkness than in daylight, while for slight injury crashes it is the other way round, it can be concluded that darkness crashes show and increased severity.

1.2 BACKGROUND

1.2.1 What is the effect of darkness on road safety?

The most obvious impact of darkness on road safety is the decreased visibility. The distance a driver can see is shortened and so hazards can sometimes seem to appear out of nowhere. Vulnerable road users in particular suffer from this reduced visibility caused by darkness, in the sens that they are less visible / identifiable than the other road users, as they are smaller and less (well) equipped with headlights. In darkness it is also harder to judge speed and distance and objects can be closer than they appear or travelling faster than first expected.

1.2.2 What is the effect of darkness on crash type?

SafetyCube crash scenario reveals that the percentage of single vehicle crashes is much higher in darkness conditions (without streetlighting) than in other lighting conditions. This trend is confirmed by the increased share of driving crashes (i.e. crashes that are initiated by a driving error (initially) without the interference of an opponent) and of crashes in bends or on straight roads. On the opposite, the share of crashes at junction is much smaller in darkness. Given that the occurrence effects are not corrected for different transport patterns (darkness is mostly coinciding with night-time), it is unclear whether these differences are due to the risk of darkness or rather due to some other characteristic of night-time crashes. Certainly the reduction of bicycle and pedestrian crashes in darkness is most likely an effect of lesser mobility of these road users at night.

1.2.3 How is the effect of darkness studied?

This synopsis focusses on the impact of darkness on road safety, defined as the total absence of light, whether natural or artificial. As darkness occures at period with, by definition, lower traffic,

priority was given to papers that study the impact of darkness on crash (injury) risk or severity rather than on mobility.
5 recent studies establishing the impact of darkness on crash risk of crash severity (in Europe) have been coded, analysed and summarised. Two of these use an ordered probit model in order to investigate the effect of darkness (amoung others) on the severity of crashes. The three others try to assess the risk of crash (or of fatality) associated with darkness. For this, they develop methods which do not require exposure data (travelled kilometers for example). They use either odds ratio or a binary logistic regression.

1.3 OVERVIEW OF RESULTS

1.3.1 Main results

Due to the large variety in outcome variables (severity versus risk, per road user type, road type or collision type, etc.) a vote-count analysis has been conducted, rather than of a meta-analysis.

Among the 34 effects of darkness on the **risk of (injury) crash** reported in the selected studies, only 6 refer to a general situation not taking into account the type of road user or the type of collision. In all cases (100%), the absence of light is associated with an increased risk of crash.
The 28 remaining effects tackle the impact of darkness on the risk of crashes by type of road user and type of collision. The only clear conclusion concerns the crash risk for pedestrians. 6 effects look at this crash type, and 5 of them (83%) conclude to an increase of crash risk for this road user. Depending on the study and the circumstances, the crash risk for pedestrian is 2 to 4 times higher in darkness than in daylight conditions. This is by far the type of road user (or the type of crash) experiencing the greatest increase in the risk of crash under darkness.
The risk of crash in darkness also seems to increase for powered two-wheelers, but only in urban areas and to a lesser extent (relative risk below 2). For cars, results do not show any significant variation of crash risk in darkness. Finally, results per collision type (almost) systematically indicate a decrease of the crash risk.

Two studies out of the selected five tackle the impact of darkness on the **severity of crashes**. Both of them evaluate the probability of sustaining one of the three injury severities in darkness, compared to daytime. It appears that fatalities and serious injuries are more likely in darkness than in daytime. But opposite results are obtained for slight injuries, which are less likely in darkness than in daylight. It can thus be concluded that darkness has an effect on the crash severity by increasing it.

1.3.2 Transferability

The size of the effects is difficult to compare across studies, because of the variety in the methods, in the outcome variables and in the dissageregation. Although the risk-effect of darkness seems to be confirmed in most studies, it is mainly found for pedestrians. In this sense, the transferability of results from one country to another is low, especially if countries have different shares of vulnerable road users.

1.4 NOTES ON ANALYSIS METHODS

Only few papers study the impact of darkness on crashes in general. Depending on the case, a distinction/selection is made according to the type of road user (pedestrians, cars, vulnerable road users, etc.), the location (urban versus rural, highways) or the crash type. Although this "disaggreagation" is preferable to understand the effect of darkness, it also implies that conclusions of the analysis performed above are based on a small number of observations.

It has to be added that when studying the effect of darkness on road safety, it's difficult to distinguish the effect due to the absence of light itself and the effect mainly related to the time period (night), such as speeding, sleepiness/tiredness and driving under the influence of alcohol or drugs.

2 Scientific overview

2.1 LITERATURE REVIEW

2.1.1 What is the effect of darkness on road safety?[1]

The most obvious impact of darkness on road safety is the **decreased visibility**. The distance a driver can see is shortened and so hazards can sometimes seem to appear out of nowhere. It also takes time for the eyes to adjust to the darkness after being in a lit building or after driving on a well-lit road. Furthermore, in low lit areas, road users may also be dazzled by the headlights of an oncoming vehicle.

Vulnerable road users in particular suffer from this reduced visibility caused by darkness, in the sens that they are less visible / identifiable than the other road users, due to their smaller size and the absence of headlights (or less powerful/numerous headlights).

In darkness it is also **harder to judge speed and distance** and objects can be closer than they appear or travelling faster than first expected.

Besides, when studying the effect of darkness on road safety, it's difficult to distinguish the effect due to the absence of light itself and the effect mainly related to the time period (night). For example, the hours of darkness are usually the hours of sleep, meaning that driver fatigue and tiredness are common at this moment. Furthermore, night, and especially weekend night, is known for its higher consumption rate of alcohol and drug amoung drivers. We can also add speeding which is more frequent during night than during other periods. Isolating the effect of the absence of light from these **confounding factors** is thus a challenge for any studies that want to study the impact of darkness.

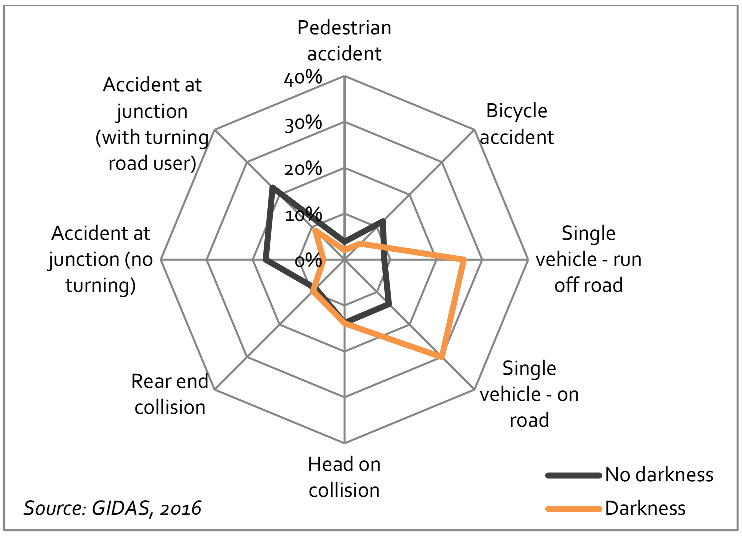
2.1.2 Crash scenarios

SafetyCube crash scenarios allow to compare crashes that occured in darkness to those that did not (Figure 1). In the figure below, the "darkness" circumstances correspond to the lighting conditions targeted in this synopsis, namely the night without streetlighting. This condition is compared to all other lighting conditions (daylight, twilight and night with lighting).

This crash scenario analysis was conducted using cases from the German In-Depth Accident Study (GIDAS) database. All crashes were considered which were ready for analysis and which were collected in the years 2007 to 2015. In total, records from 14.398 crashes which occurred in the regions of Hannover and Dresden were analysed. The GIDAS database details those crashes which occurred on a public road where at least one person was injured. The crashes are collected according to a statistical sampling process to ensure a high level of representativeness of the actual crash situation in the sample regions. The data collection is conducted using the "on the scene" approach where all factors which were present at a crash are recorded. This does not mean that the recorded factor was a contributory factor towards the crash. For the current analysis all crashes where darkness (night without lights) was listed as present at the crash scene were compared to all crashes where such darkness was no present at the crash scene.

[1] Inspired by http://www.rospa.com/road-safety/advice/drivers/better-driving/night

Figure 1 Share of the different crash types under darkness and "no darkness" lighting conditions



In darkness conditions without streetlighting, the percentage of single vehicle crashes is much higher than in other lighting conditions, as well single crashes on road as the ones with a vehicle running off the road. In such darkness conditions, more than half of the analysed German crashes are single vehicle crashes. This trend is confirmed by the increased share of driving crashes (i.e. crashes that are initiated by a driving error (initially) without the interference of an opponent) and of crashes in bends or on straight roads observed in the GIDAS data when it's dark (not shown here). On the opposite, the share of crashes at junction is much smaller in darkness. Note that these results could partially be explained by the low traffic during night, what results in a lower probability to cross another roaduser (and to hit it). It could also derive from a different road user's behaviour at night (speed, fatifue, driving under influence of alcohol/drug, etc.).

As under adverse weather conditions, crashes with bicyle are less frequent when it's dark. It's here also the case of pedestrian crashes. It could be explained by a reduced traffic of vulnerable road user in such conditions.

2.2 DESCRIPTION OF STUDIES

2.2.1 How (well) is the effect of darkness studied?

For the present overview the focus is on recent (from 1990 to current) European studies. As darkness occures at period with, by definition, lower traffic, priority was given to papers that study the impact of darkness on crash (injury) risk or severity rather than on mobility. Darkness is here defined as the total absence of light, whether natural or artificial[2]. So, only studies tackling the impact of "night without lighting" have been selected. As defining darkness based on the hour does not guarantee the absence of light, this definition was also excluded of the selection.

Because of these strict selection criteria, only five articles were selected for further analysis. Two of these use an ordered probit model in order to investigate the effect of darkness (amoung others) on the severity of crashes. The three others try to assess the risk of crash (or of fatality) associated with darkness. For this, they develop methods which do not require exposure data (travelled kilometers for example). They use either odds ratio or a binary logistic regression.

Only few papers study the impact of darkness on crashes in general. Depending on the case, a distinction/selection is made according to the type of road user (pedestrians, cars, vulnerable road

[2] The impact of lighting is discussed in a distinct synopsis, as a road safety measure.

users, etc.), the location (urban versus rural, highways) or the crash type. Although this "disaggreagation" is preferable to understand the effect of darkness, it also implies that conclusions of the analysis performed below are based on a small number of observations.

2.2.2 Transferability

The size of the effects is difficult to compare across studies, because of the variety in the methods, in the outcome variables and in the dissageregation. Although the risk-effect of darkness seems to be confirmed in most studies, it clearly differs according to road user type and the road type.
In this sense, the transferability of results from one country to another is relatively low, especially if countries have a different share of road users (in particular pedestrians).

2.3 DESCRIPTION OF ANALYSIS CARRIED OUT

2.3.1 Vote-count analysis

5 key studies establishing the risk and severity impact of darkness in European countries have been coded, analysed and summarized. Although a total of 46 effects are reported in these studies, the large variety in outcome variables (severity versus risk, per road user type, road type or collision type, etc.) does not allow a meta-analysis of the results. Instead a vote-count analysis has been conducted: each test that is executed in one of the studies has one vote on the effect of darkness. The vote can take three different values:

- An increase in either the crash risk or the crash severity (↗)
- A decrease of the indicator (↘)
- No significant impact in the indicator (-)

These vote-counts are analysed with respect to different characteristics of the dependent variables. The most important distinction is the one made between the impact on risk (34 effects reported) and the impact on severity (12 effects reported). Sub-distinctions are thereafter made per road user type and per collision type.

2.3.2 Impact of darkness on crash risk

Global impact

Among the 34 effects of darkness on the risk of (injury) crash reported in the selected studies, only 6 refer to a general situation not taking into account the type of road user or the type of collision. In all cases (100%), the absence of light is associated with an increased risk of crashes. This occurs in both rural and urban areas, and both during morning and evening darkness periods. Depending on the study, the injury risk is from 10 to 60% higher in darkness (night without light) than in daytime.

Table 1 Vote-count analysis results for global crash risk

Author(s)	Road user	Rural/urban	Road type	Timing	Effect on road safety
Johansson et al.	All	Urban			↗
Johansson et al.	All	Rural			↗
Gaca et al.			National road	Morning (05-06h)	↗
Gaca et al.			Regional road	Morning (05-06h)	↗
Gaca et al.			National road	Evening (17-19h)	↗
Gaca et al.			Regional road	Evening (17-19h)	↗

Impact per road user type and collision type

The 28 remaining effects tackle the impact of darkness on the risk of crashes by type of road user and type of collision. The only clear conclusion concerns the crash risk for pedestrians. 6 effects look at this crash type, and 5 of them (83%) conclude to an increase of crash risk for this road user (unsignificant result for the last one (relative risk for pedestrian in rural area)). Depending on the study and the circumstances, the crash risk for pedestrian is 2 to 4 times higher in darkness than in daylight conditions. This is by far the type of road user (or the type of crash) experiencing the greatest increase in the risk of crash under darkness.

Table 2 Vote-count analysis results for pedestrian crash risk

Author(s)	Road user	Rural/urban	Road type	Collision type	Timing	Effect on road safety
Johansson et al.	Pedestrian	Urban				↗
Johansson et al.	Pedestrian	Rural				-
Gaca et al.			National road	Pedestrian		↗
Gaca et al.			Regional road	Pedestrian		↗
Olszewski et al.	Pedestrian				Dark no lighting	↗
Olszewski et al.	Pedestrian				Twilight	↗

In agreement with these findings, in Poland, the only crash type that showed an increased risk in darkness were pedestrian crashes, while all other types showed a slight decrease in risk (Gaca & Kiec, 2013). This shows that – at least for Poland – the observed increased crash risk due to darkness is entirely due to a higher risk for pedestrian crashes.

Table 3 Vote-count analysis results for crash risk per collision type

Author(s)	Road type	Collision type	Effect on road safety
Gaca et al.	National road	Pedestrian crash	↗
Gaca et al.	National road	Head-on collision	↘
Gaca et al.	National road	Side collision	↘
Gaca et al.	National road	Rear-end collision	↘
Gaca et al.	National road	Hitting other vehicle	↘
Gaca et al.	National road	Hitting the animal	[?]
Gaca et al.	National road	Rollover	↘
Gaca et al.	National road	Hitting the obstacles	↘
Gaca et al.	National road	Others	↘
Gaca et al.	National road	Pedestrian crash	↗
Gaca et al.	Regional road	Head-on collision	↘
Gaca et al.	Regional road	Side collision	↘
Gaca et al.	Regional road	Rear-end collision	↘
Gaca et al.	Regional road	Hitting other vehicle	-
Gaca et al.	Regional road	Hitting the animal	[?]
Gaca et al.	Regional road	Rollover	↘
Gaca et al.	Regional road	Hitting the obstacles	↘
Gaca et al.	Regional road	Others	↘

In a joint analysis of Sweden, Norway, and the Netherlands, the risk of crash in darkness also seems to increase for powered two-wheelers, but only in urban areas (Johansson, Wanvik, & Elvik, 2009), and to a lesser extent than for pedestrians (relative risk below 2). For cars, results do not show any significant variation of crash risk in darkness, whether in rural or in urban areas (Johansson et al., 2009).

Table 4 Vote-count analysis results for crash risk per road user type (other than pedestrians)

Author(s)	Road user	Rural/urban	Effect on road safety
Johansson et al.	Cyclist	Urban	↗
Johansson et al.	Motorcyclist	Urban	↗
Johansson et al.	Car	Urban	-
Johansson et al.	Cyclist	Rural	-
Johansson et al.	Motorcyclist	Rural	-
Johansson et al.	Car	Rural	-

2.3.3 Impact of darkness on crash severity

Two studies out of the selected five tackle the impact of darkness on the severity of crashes (Gray, Quddus, & Evans, 2008) (Michalaki, Quddus, Pitfield, & Huetson, 2015). Both of them evaluate the probability of sustaining one of the three injury severities in darkness, as compared to daytime. The table below summarizes the 12 effects reported in these studies. It clearly appears that more severe injuries are predicted during darkness, or, in other words, that fatalities and serious injuries are more likely in darkness than in daytime. But opposite results are obtained for slight injuries, which are less likely in darkness than in daylight. It can thus be concluded that darkness has an effect on the crash severity by increasing it.

Table 5 Vote-count analysis results for crash severity

		Slight injury	Serious injury	Fatal injury
Young male car driver – GB	Gray et al.	↘	↗	↗
Young male car driver – London	Gray et al.	↘	↗	↗
Motorway – Main carriageway	Michalaki et al.	↘	↗	↗
Motorway – Hard shoulder	Michalaki et al.	↘	↗	↗

2.4 CONCLUSION

The synopsis focusses on the impact of darkness on road safety, defined as the total absence of light, whether natural or artificial. 5 recent studies establishing the impact of darkness on crash risk of crash severity (in Europe) have been coded, analysed and summarised. Due to the large variety in outcome variables (severity versus risk, per road user type, road type or collision type, etc.) a vote-count analysis has been conducted, rather than a meta-analysis.

When looking at the impact of darkness on the global **crash risk**, results show that the absence of light is associated with an increased risk of crashes. But the impact on risk clearly differs according to road user type and the road type. The clearest conclusion concerns the crash risk for pedestrians, which is 2 to 4 times higher in darkness than in daylight conditions. The risk of crash in darkness also seems to increase for powered two-wheelers, but only in urban areas and to a lesser extent (relative risk below 2). For cars, results do not show any significant variation of crash risk in darkness. Finally, results per collision type show opposite results with an (almost) systematic decrease of the crash risk.

About the impact of darkness of the **severity of crash**, the two studies analysing this effect indicate that fatalities and serious injuries are more likely in darkness than in daytime, but that slight injuries are less likely in darkness than in daylight. It can thus be concluded that darkness has an effect on the crash severity by increasing it.

It has to be added that when studying the effect of darkness on road safety, it's difficult to distinguish the effect due to the absence of light itself and the effect mainly related to the time period (night), such as speeding, sleepiness/tiredness and driving under the influence of alcohol or drugs. None of the selected papers seems to try to struggle against the effect of these confounding factors. Furthermore, due to the "dissagregation" of the results per road user type and other key-variables, the conclusions of the analysis performed above are based on a small number of observations. These thus have to be interpreted prudently.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature search strategy

Principles

The literature search was focused on darkness as risk factor, and not on lighting which is deeply studied in the deliverable dedicated to the road safety measures.
Darkness is here considered as the total absence of light, whether natural or artificial. Only studies tackling the impact of "night without lighting" have been selected. In order to clearly identify darkness, papers that defined darkness based on the hour (nighttime), without any other consideration, were excluded.

Excluded:

- Impact of road lighting on road safety or of other countermeasures to darkness
- Impact on mobility, traffic/transport/flow, driver's behaviour (speed, etc.), vehicle's behaviour (deviation, etc.)
- Descriptive analyses of crashes

Research terms and hits

Database: Scopus **Date:** 19th and 22nd of August 2016

Limitations/ Exclusions:

- Search field: TITLE-ABS-KEY
- Published: 1990 to current
- Document Type: ALL
- Subject Area: ALL

search no.	search terms / operators / combined queries	hits
#1	(TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities") AND TITLE-ABS-KEY (dark OR darkness OR lighting OR light OR visibility))	2241 Too many hits → limitation of research field in attempt n°2
#2	(TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities") AND TITLE-ABS-KEY (darkness OR lighting OR visibility))	783
#3	(TITLE-ABS-KEY ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities") AND TITLE-ABS-KEY ("night driving" OR daylight OR nighttime OR daytime OR night-time OR day-time) AND NOT TITLE-ABS-KEY (running) AND NOT TITLE-ABS-KEY (apnoea OR apnea OR insomnia))	735

Database: TRID **Date:** 22nd of August 2016

Limitations/ Exclusions:

- Published: 1990 to 2016
- Document source : ALL, Document Type: ALL, Subject area : ALL
- Language: English

search no.	search terms / operators / combined queries	hits
#1	Darkness "road safety"+ Darkness "road accident" + Darkness "accident risk"	232 + 74 + 26

Database: ScienceDirect **Date:** 22nd of August 2016

Limitations/ Exclusions:

- Search field: Abstract, title, keywords
- Published: 1990 to current
- Document Type: ALL
- Subject Area: ALL

search no.	search terms / operators / combined queries	hits
#1	TITLE-ABSTR-KEY(darkness) and TITLE-ABSTR-KEY("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities").	15
#2	TITLE-ABSTR-KEY(nighttime or night-time) and TITLE-ABSTR-KEY("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "accident risk" OR "crash risk" OR "road fatalities")	123

Results Literature Search

Database	Hits
Scopus	1518
TRID	332
ScienceDirect	138
Total number of studies to screen title	**1988**

Screening

Total number of studies to screen title (in order to evaluate the relevance to the topic)	1988
Number of articles remaining after screening of the title and the abstract	38

Prioritizing Coding

Prioritization:

1. Priority to Meta-analyse
2. Selection of studies from Europe

3. Priority to studies about risk or severity
4. Exclusion of studies defining "darkness" based on time (hour) without any other consideration

Following these prioritization criteria, the full-text screening of the 38 studies has allowed to select 5 papers to be coded*.

Table 6 Final list of coded studies

Authors	Title	Year	Country
Gray, R., Quddus, M., Evans, A.	Injury severity analysis of accidents involving young male drivers in Great Britain	2008	UK
Johansson, Ö., Wanvik, P.O., Elvik, R.	A new method for assessing the risk of accident associated with darkness Includes : - Johansson, Ö. 2007. Metodrapport. Vägverket, Publikation 2007:82. Vägverket, Borlänge - Wanvik, P.O., 2009. Effects of road lighting. An analysis based on Dutch accident statistics 1987–2006, Accident Analysis and Prevention 41n 123-128	2009	Norway, Sweden, Netherlands
Gaca S., Kiec, M.	Risk of accidents during darkness on roads with different technical standards	2013	Poland
Olszewski P., Szagała P., Wolański M., Zielińska A.	Pedestrian fatality risk in accidents at unsignalized zebra crosswalks in Poland	2015	Poland
Michalaki, P., Quddus, M., Pitfield, D., Huetson, A.	Exploring the factors affecting motorway accident severity in England using the generalised ordered logistic regression model	2015	England

* The paper "De Oña J., Mujalli R.O., Calvo F.J. (2011) Analysis of traffic accident injury severity on Spanish rural highways using Bayesian networks" was first selected for coding, but as further calculations are needed to exploit the information it contains, it was decided to leave it out.

3.1.2 Description of coded studies and sampling frames

Table 7 Characteristics of coded studies

Authors	Period covered	Country	Aim	Methodology / Design	Outcome variable	Type of crash	Lighting classification	Other variables
Gray, R., Quddus, M., Evans, A.	1991-2003	Great Britain as a whole + London only	Investigating the factors affecting the severity of crashes probability of sustaining one of three injury severities	Ordered probit model	Severity categorized as fatal, serious, or slight.	Crashes involving young (17-25) male car drivers	• Daylight • Darkness	20 other independant variables
Johansson, Ö., Wanvik, P.O., Elvik, R.	1997-2006 1996-2005 1987-2006	Sweden Norway Netherlands	Assessing the risk of crashes associated with darkness	Odds ratio*	Relative risk of injury crash associated with darkness (compare to risk in daylight)	Injury crash, per road user (pedestrian, cyclist, motorcyclist, car, all) and per area type (urban / rural / all)	Based on hour and sunrise / sunset	/
Gaca S., Kiec, M.	2005-2009	Poland	Assessing the risk of crashes associated with darkness	Odds ratio*	Relative risk of injury crash associated with darkness (compare to risk in daylight)	Road crashes (without any precision), per road type (national / regional) and collision type	Based on hour and sunrise / sunset	/
Olszewski P., Szagała P., Wolański M., Zielińska A.	2007-2012	Poland	Identifying main factors contributing to the high fatality rates at pedestrian at crosswalks	Binary logistic regression (with interaction terms)	Pedestrian fatality risk, defined as pedestrian's risk of being killed when hit by a vehicle while crossing a road	Pedestrian injuring crashes on unsignalized marked zebra crosswalks	• Daylight • Dark no lighting • Dark steet lights • Twilight	7 other independant variables
Michalaki, P., Quddus, M., Pitfield, D., Huetson, A.	2005-2011	Great Britain (England)	Identifying any differences between the factors that contribute to the severity of HS (hard shoulder) and MC (main carriageway) motorway crashes	Generalized ordered logit model	Severity of crash, categorized as fatal, serious, or slight.	Injury crashes on motorways	• Daylight • Dark and lights on • Dark and no lights	About 15 other independent variables

$$* \frac{\text{Number of accidents in darkness in a given hour of the day} / \text{Number of accidents in daylight in the same hour of the day}}{\text{Number of accidents in a given comparison hour when the case hour is dark} / \text{Number of accidents in a given comparison hour when the case hour is in daylight}}$$

3.2 ANALYSIS OF THE STUDY RESULTS

3.2.1 Detailed overview of the results

Table 8 gives the main results of each coded study. The effects on road safety are coded as

↗ = significant increase of crash/victim numbers or of crash risk = threat to road safety

↘ = significant decrease of crash/victim numbers or of crash risk = improvement of road safety

- = no significant change

Table 8 Detailed overview of the results of the different selected studies

Authors	Outcome variable	Geographical area	Severity outcome	Rural/urban	Percentage change	Effect on road safety	Main outcome - Description
Gray, R., Quddus, M., Evans, A.	Severity of crash	Great Britain	Slight injury		-5%	↘	• More severe injuries are predicted during darkness, with fatalities 30%/23% more likely and serious injuries 13%/11% more likely than in the reference case (daylight). • But opposite result for slight injuries (5%/3% less likely in darkness than in daylight)
			Serious injury		+13%	↗	
			Fatal injury		+30%	↗	
		London	Slight injury	[Urban]	-3%	↘	
			Serious injury	[Urban]	+11%	↗	
			Fatal injury	[Urban]	+23%	↗	

Authors	Outcome variable	Road user	Rural/urban	Relative risk [odds ratio]	Effect on road safety	Main outcome - Description
Johansson, Ö., Wanvik, P.O., Elvik, R.	Relative risk of crash	Pedestrian	Urban	2.08	↗	• The risk of injury crashes increases by 30 % in darkness in urban areas and 50 % in rural areas, but mostly so for pedestrians. • The risk for cyclists was also found to increase, but the study found no change in risk for car occupants.
		Cyclist	Urban	1.52	↗	
		Motorcyclist	Urban	1.55	↗	
		Car	Urban	0.94	-	
		All	Urban	1.28	↗	
		Pedestrian	Rural	2.29	-	
		Cyclist	Rural	2.37	-	
		Motorcyclist	Rural	2.08	-	
		Car	Rural	1.21	-	
		All	Rural	1.47	↗	

Authors	Outcome variable	Road type	Collision type	Timeslot	Relative risk [odds ratio]	Effect on road safety	Main outcome - Description
Gaca S., Kiec, M.	Relative risk of crash	National road	Head-on collision		0.89	↘	• The influence of darkness on road safety in darkness (17:00 – 19:00 Case 2 and 18:00 – 19:00 Case 3) is far greater. • During the morning hours (Case 1 – 5:00 – 6:00) the lack of natural light resulted in only a 6% increase on national roads. • The crashes involving pedestrians strongly increases in darkness
			Side collision		0.59	↘	
			Rear-end collision		0.8	↘	
			Pedestrian		4.9	↗	
			Hitting other vehicle		0.58	↘	
			Hitting the animal		2.0	[?]	
			Rollover		0.58	↘	
			Hitting the obstacles		0.58	↘	
			Others		0.74	↘	
		Regional road	Head-on collision		0.68	↘	
			Side collision		0.39	↘	
			Rear-end collision		0.34	↘	
			Pedestrian		4.54	↗	
			Hitting other vehicle		1.33	-	
			Hitting the animal		1.33	[?]	
			Rollover		0.24	↘	

			Hitting the obstacles		0.56	↘	
			Others		0.52	↘	
		National road		Morning (05-06h)	1.06	↗	
		Regional road		Morning (05-06h)	1.31	↗	
		National road		Evening (17-19h)	1.65	↗	
		Regional road		Evening (17-19h)	1.26	↗	

Authors	Outcome variable	Timing	Relative risk [odds ratio]	Effect on road safety	Main outcome - Description
Olszewski P., Szagała P., Wolański M., Zielińska A.	Pedestrian fatality risk [Severity of crash]	Dark no lighting	3.92	↗	• The odds of death as a result of pedestrian being hit in darkness (dark, no street lighting) are 3.9 times higher when compared to daylight conditions.
		Twilight	1.84	↗	

Authors	Outcome variable	Severity outcome	Road type	Estimated probability [marginal effect]*	Effect on road safety	Main outcome - Description
Michalaki, P., Quddus, M., Pitfield, D., Huetson, A.	Severity of crash	Slight injury	Motorway – Main carriageway	0.0271	↘	• The presence of light (daylight or street lighting) has an effect on the crash severity by decreasing it; thus it is expected to have lower severity crashes when visibility on the motorway is better.
		Serious injury	Motorway – Main carriageway	-0.0181	↗	
		Fatal injury	Motorway – Main carriageway	-0.0090	↗	
		Slight injury	Motorway – Hard shoulder	0.0995	↘	
		Serious injury	Motorway – Hard shoulder	-0.0729	↗	
		Fatal injury	Motorway – Hard shoulder	-0.0265	↗	

** Attention in this study, unlike in other studies, darkness (dark and no light) is the reference case.*

3.3 FULL LIST OF CODED STUDIES

Gaca, S., & Kiec, M. (2013). Risk of accidents during darkness on roads with different technical standards. In *16th Road Safety on Four Continents Conference - Beijing China 15-17 May 2013*.

Gray, R. C., Quddus, M. A., & Evans, A. (2008). Injury severity analysis of accidents involving young male drivers in Great Britain. *Journal of Safety Research*, *39*(5), 483–495. http://doi.org/10.1016/j.jsr.2008.07.003

Johansson, Ö., Wanvik, P. O., & Elvik, R. (2009). A new method for assessing the risk of accident associated with darkness. *Accident Analysis and Prevention*, *41*(4), 809–815. http://doi.org/10.1016/j.aap.2009.04.003

Michalaki, P., Quddus, M. A., Pitfield, D., & Huetson, A. (2015). Exploring the factors affecting motorway accident severity in England using the generalised ordered logistic regression model. *Journal of Safety Research*, *55*, 89–97. http://doi.org/10.1016/j.jsr.2015.09.004

Synopsis 11: Presence of workzones- Workzone length

1 Summary

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September 2016

COLOUR CODE: RED

The presence of long workzones is intuitively considered as a risk factor, since more crashes are likely to occur in extensive work zone areas (increased crash risk). This result was reported by all coded studies, which have show a consistent negative effect on the number of crashes (increased crash risk) and was also confirmed by the meta-analysis carried out. One study also indicates that increased lengths of work zones increase the probability of crash occurrence.

KEYWORDS

Work zones; length; crashes

1.1 ABSTRACT

It can be assumed that long work zones may increase risk of crashes, because work zones are unfamiliar road environments for most road users, due to special arrangements (lane closures, traffic disruptions, changes in road delineation and signage, presence of barriers, obstacles, workers etc.). In general, work zone length was found to significantly increase the number of crashes. The vast majority of international literature investigates crash frequency, indicating that longer work zone lengths in road networks are associated with an increased number of crashes at a 95% confidence level. This result is confirmed by the meta-analysis that was carried out, which revealed a significant overall estimate of work zone length. Moreover, only one study that investigates crash risk (probability of crash occurrence vs non-crash occurrence) was found, suggesting that work zone length significantly increases crash risk.

1.2 BACKGROUND

1.2.1 Definitions of workzone length

This risk factor has a straightforward definition in international literature. It is defined as "work zone length" and examined as numerical variable measured in miles or kilometers. However, a number of studies measure it as the natural logarithm of length, for modelling purposes.

1.2.2 How does work zone length affect road safety?

It is expected that long work zones may increase risk of crashes, because work zones are unfamiliar road environments for most road users, due to special arrangements (lane closures, traffic disruptions, changes in road delineation and signage, presence of barriers, obstacles, workers etc.). Therefore, driver exposure to such risky elements increases.Consequently, it is likely that they pose a greater threat to the safety of road users than regular road segments. Therefore, presence of such arrangements for long road segments can deteriorate road safety levels.

1.2.3 Which safety outcomes are affected by work zone length?

In international literature, the effect of work zone length on road safety has been measured mainly on the basis of crash frequency (number of crashes occurred). Less frequently, it was found to be measured as crash risk (probability of crash occurrence versus probability of non-crash occurrence[1]) . It is noted that no studies concerning crash or injury severity were identified through the literature search.

1.2.4 How is the effect of work zone length studied?

In general, when the impact of work zone length is examined, crash data from police records are usually utilized. Regarding the methods of analysis, the effect of workzone length is usually examined by applying multivariable linear statistical models. When crash frequency is examined, the relationship between work zone length and number of crashes is investigated by applying Negative binomial models. Probability of crash occurrence was investigated by applying rare-events logistic regression models.

1.3 OVERVIEW OF RESULTS

The initial examination of relevant studies suggests that the effect of work zone length on road safety is generally consistent, showing that when work zones have increased length the number of crashes is increased. The same direction of the effect is observed when crash risk is examined (probability of crash occurrence vs non crash occurrence[2]), where there is also a negative effect of work zone length on safety.

Almost all examined studies are based on data from highways in 3 States of the US (Indiana, New Jersey and California). One study examines urban and non-urban roads (Khattak et al., 2002). Moreover, little is known about various road users as the number of total crashes is investigated and transferability is not certain. These studies applied a similar modeling approach (models for count data) and considered similar control variables (environmental, traffic etc.), but used different modeling specifications (e.g. Poisson models, fixed vs random effects negative binomial models etc). Moreover, different measurement units were used (miles, kilometres etc.). Yang et al. (2015) examined the probability of crash occurrence and applied rare-events logistic regression.

Therefore, after applying the appropriate transformations, it was attempted to apply a random effects meta-analysis for the effect of work zone length on crash frequency by considering studies which have the same model specification (i.e. fixed effects negative binomial models). The results suggested that increased workzone length significantly increases the number of crashes for a 95% level of confidence. The overall estimate for the beta coefficient of the effect of work zone length on crash frequency was found to be 0.862, which was considered to be statistically significant (see Figure 1). No publication bias was found to exist. Moreover, a meta-regression was applied in order to identify which study characteristics (moderator variables) affect the overall estimate. The results indicate that the year of the study and the model specification are the core predictors of the overall estimate. More specifically, recent studies and studies utilizing more simple models are likely to provide lower estimates (smaller influence of WZ length on safety).

1.4 NOTES ON ANALYSIS METHODS

In general, the examined studies are of sufficient quality and metholologically sound and advanced. The only potential bias indicated in some of the studies, is the fact the applied statistical methods and model specifications (fixed effects models) do not account for unobserved heterogeneity[3] that is possibly present, because they assume the effect of the explanatory variable (work zone length)

[1] Time periods with and without crashes were selected for comparison and estimation of crash risk.The reader is encouraged to refer to Yang et al. (2015).

[3] For more details, the reader is encouraged to refer to Karlaftis and Tarko (1998) and Washington et al. (2010).

on the frequency of crashes is constrained to be the same for all observations (all work zone segments). Consequently, the resulting parameter estimates may be biased.

Overall, this risk factor could be considered to be adequately studied. However, there are no studies focusing on the effect of work zone length on crash or injury severity. Moreover, they all concern states of the US and there is no specific focus on different road users. In conclusion, data concerning more countries and different road users are needed.

2 Scientific overview

2.1 LITERATURE REVIEW

The transportation network is frequently affected by the disruptions caused by work zones associated with construction, maintenance, and rehabilitation projects. Such issues are particularly notable for critical freeways and arterials. The literature search shows that there is evidence that work zones a hazardous roadway environment to drivers that increases the risk of road crashes and injuries. The reduction of number and capacity of road lanes, the changes in road delineation and signage, the presence of workers, construction machinery, roadside construction barriers and other objects and obstacles, may create a core complex environment with increased conflicts that in turn lead to high risk conditions. Thus, the safe and efficient movement of drivers through work zones is a major concern to transportation engineers, road industry and researchers.

The literature search showed that there are a lot of studies examining road safety of workzones. However, the number of studies using quantitative methods in order to acquire relationships between work zone characteristics and road safety indicators are not many. In addition, some risk factors (e.g. work zone duration and length) have not adequately been explored, as many studies take into account behavioural and other geometrical parameters from police records regarding crashes in work zones. In general, crash data from police records are usually utilized to study the impact of work zone length. Chen and Tarko (2014), argue that work zone information and data should be better reported in crash police records. Another issue mentioned by the authors is the limited data availability regarding work zone characteristics asdetailed road cross-section data and traffic management plans are not readily available.

Work zone length is one of the main risk factors associated with work zone characteristics. It is defined as a numerical variable measured in miles or kilometers. Moreover, a couple of studies measure it as the natural logarithm or the logarithm of length.

In general, it is suggested that increased work zone lengths are more risky. More specifically, Khattak et al. (2002) quantified the effect of work zone length on non-injury and injury crashes on the basis of California crash data for 1992 and 1993. The authors found that length increases the numbers of both non-injury and injury crashes. A similar study by Ozturk et al. (2013) used 2004-2010 accdent data in work zones of New Jersey states and argued that increased length causes more crashes in work zones. Chen and Tarko (2012) examined 3 year of work zone crashes and indicated that increased lengths increase number of crashes. Similar findings were reported in (Chen and Tarko (2014). Venugopal and Tarko (2000) investigated the effect of work zone characteristics on the crash frequencies for different injury severity levels and found similar findings for all severity levels considered. The same results were suggested by Ozturk et al. (2014). However, they have also applied different models separately for night and day crashes. Yang et al. (2013), examined frequency of property-damage only and injury crashes by applying Bayesian negative binomial models and found a consistent positive influence (increase in numbers) of work zone length on crashes for different severity levels. Yang et al. (2015) investigated crash risk and found that the probability of crashes is higher when work zone length is high.

Regarding the methods of analysis, the effect of workzone length is usually examined by applying multivariable linear statistical models. When crash frequency is examined, the relationship between length and number of crashes is investigated by applying various models (e.g. Bayesian negative binomial, fixed effects negative binomial, Poisson etc.). Probability of crash occurrence was investigated by applying rare-events logistic regression models.

Overall, this topic is not extensively investigated and this may be mainly attributed to two reasons: a) the small available samples of crashes during the works (due to the usually short duration of work zones) and b) the small samples of relevant data after the end of the work zone (also due to the improvement of the safety level).

2.2 DESCRIPTION OF AVALIBLE STUDIES

2.2.1 Analysis of study designs and methods

Eight high quality studies were selected and coded. Seven studies had a focus on crash frequency (Khattak et al., 2002; Ozturk et al., 2013; Ozturk et al., 2014; Venugopal and Tarko, 2000; Chen and Tarko, 2012; Chen and Tarko, 2014; Yang et al., 2013). On the other hand, 1 study was found which examined the influence of work zone length on the probability of crash occurrence (Yang et al., 2015). In order to examine the underlying relationships between work zone length and those outcome indicators, all studies deployed appropriate multivariable statistical models for count data and controlled for other geometrical characteristics, traffic flow, number of lanes and other crash related variables.

All those studies which investigate crash frequency, indicate a significant effect of length on the number of crashes, regardless of the severity level (non-injury crashes, total crashes etc.) or the location of the study (States of New Jersey, California or Indiana). Interestingly, there is no distinction between road user groups as all road users of highways are considered in the analyses (or no detailed information is provided). However, Ozturk et al. (2014) makes a distinction between daytime and nighttime crashes.

Some studies used the logarithm or the natural logarithm of work zone length. Although all studies were in US states, therefore a few studies measured the work zone length in kilometers (e.g. Khattak et al., 2002; Venugopal and Tarko, 2000). In terms of methodologies, it is remarkable that some studies deployed advanced statistical methods. For example, Yang et al. (2015) used full Bayesian negative binomial models, while Chen and Tarko (2014) used random effects and random parameter negative binomial models. On the other hand, the majority of research on this topic relied on more straightforward methods.

The studies that investigated the relationship between work zone length and number of crashes utilized data from the US (mainly examining different state in each study) and confirmed that as length of work zones increases, there is an increase in the number of crash occurred. The same effect of work zone length on crash risk (probability of crash occurrence) is suggested by Yang et al. (2015).

Table 1 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 1 Description of coded studies

Author(s), Year	Sample and study design	Method of analysis	Unit of analysis	Outcome indicator	Main result
Khattak et		Fixed effects	Natural	Crash frequency	Increased work zone

al., 2002	2038 total crashes in 36 work zone sites in Indiana state, US, for the years 1992 and 1993.	negative binomial models	logarithm of length in km	(number of no injury, injury and total crashes)	length leads to increased number of all types of crashes.
Ozturk et al., 2013	5382 total crashes in New Jersey State, US for the period 2004-2010.	Fixed effects negative binomial models	Natural logarithm of length in miles	Crash frequency (number of crashes)	Increased work zone length leads to increased number of crashes.
Ozturk et al., 2014	8749 crashes in 60 work zone sites in New Jersey state,US, for the period 2001-2011	Fixed effects negative binomial models	Length in miles	Crash frequency (number of no injury and injury crashes)	Increased work zone length leads to increased number of crashes.
Chen and Tarko, 2012	2722 crashes in Indiana state, US, for the period 2008-2010	Random effects negative binomial models	Logarithm of length in miles.	Crash frequency (number of crashes)	Increased work zone length leads to increased number of crashes.
Chen and Tarko,2014	547 crashes in 72 work zone sites in Indiana state, US, for 2009	Random effects and random parameters Poisson models	Logarithm of length in miles.	Crash frequency (number of crashes)	Increased work zone length leads to increased number of crashes.
Yang et al., 2013	Crashes in 60 work zone sites in New Jersey state, US, for the period 2004-2010	Bayesian negative binomial models	Natural logarithm of length in miles.	Crash frequency (number of crashes)	Increased work zone length leads to increased number of crashes.
Venugopal and Tarko, 2000	5025 total crashes in work zones in Indiana State, US, for the period 1993-1997.	Fixed effects negative binomial models	Length in miles.	Crash frequency (number of no injury, injury and total crashes)	Increased work zone length leads to increased number of all types of crashes.
Yang et al. 2015	466 work zones with 44 crashes in New Jersey state, US, for the year 2011.	Rare-events logistic regression	Logarithm of length in miles	Crash risk (crash vs non-crash occurrence)	Increased work zone length leads to increased risk of crash occurrence.

2.3 ANALYSIS METHODS AND RESULTS

2.3.1 Introduction

A meta-analysis has been carried out in order to find the overall estimate of work zone length on crash frequency. The reasons for this decision is that:

a) A minimum required number of studies is achieved (3)
b) Studies that were considered used the same model specification (fixed effects negative binomial model)
c) The sampling frames were similar

Moreover, a meta-regression was applied in order to identify the study characteristics influencing the overall estimate.

2.3.2 Overall estimate for crash frequency

Results of the random-effects meta-analysis indicate that the overall estimate of the effect of work zone length (in Km) is 0.862 and the 95% confidence intervals are 0.810 and 0.913 respectively (Table 2). This effect was found to be 95% significant (p-value=<0.001). Figure 1 presents the forest plot.

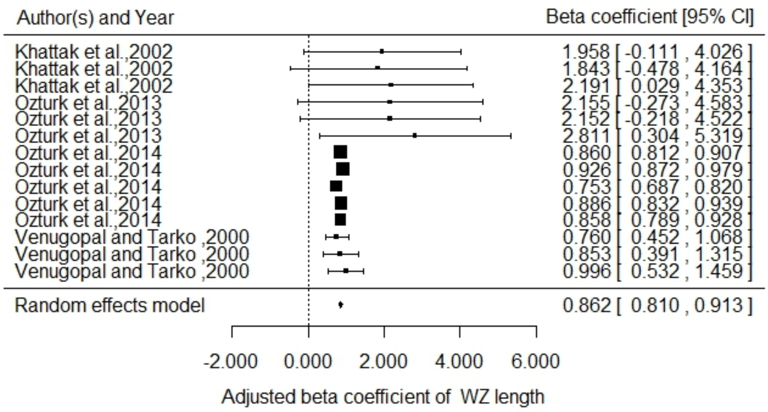

Figure 1 Forest plot of the effect of work zone length (in km) on crash frequency.

Table 2 Random effects meta-analyses for work zone effects on crash frequency.

Variable	Unit	Estimate	Std. Error	p-value	95% CI
Length	km	0.862	0.0261	<0.0001	(0.810, 0.913)

2.3.3 Heterogeneity

The Q test is significant (Q= 24.9349, p-value = 0.0235) suggesting considerable heterogeneity among the true effects.

2.3.4 Publication Bias

A funnel plot was firstly produced in order to detect potential publication bias. No publication bias exists.The regression test for funnel plot asymmetry was not significant (t-value = 1.5577, p-value = 0.1453) suggesting no publication bias. Figure 2 illustrates the funnel plot.

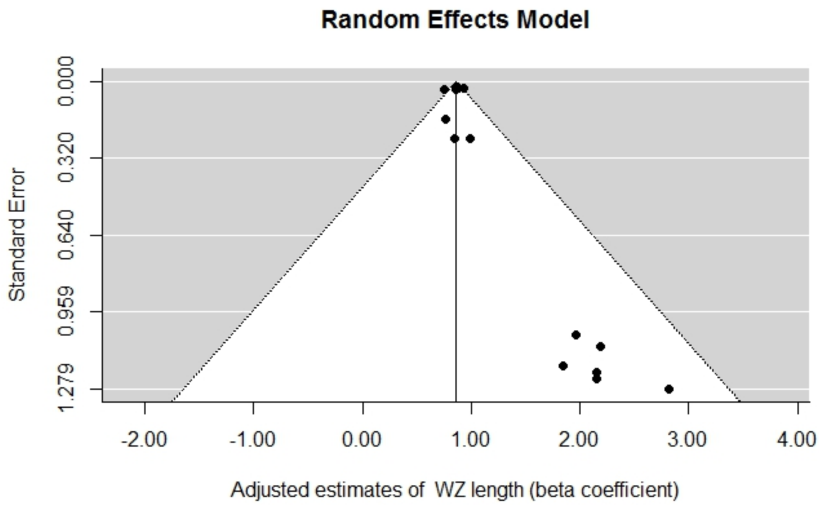

Figure 2 Funnel Plot (without correcting for publication bias).

2.3.5 Meta-regression

In order to identify the effect of the study characteristics (moderator variables) on the overall estimate, a meta-regression model was developed. Results of the meta-regression model of the effects of work zone length are shown in Table 3. It was found that the main moderator variables (study characteristics) affecting the overall estimate of work zone length are the year and model specification. More specifically, the sign of the beta coefficient of the year of the study, shows that more recent studies are more likely to report lower estimates. The negative sign of the beta coefficient of 'fixed effect' is negative, implying that studies applying fixed effects negative binomial models, report lower estimates than studies using more complex models (e.g. random effects or random parameters).

Table 3 Summary estimates of meta-regression model for work zone length.

Moderator Variable	Estimate	Standard error	p-value
Constant term	32.320	8.099	0.000
Year	-0.016	0.004	0.000
Fixed effects	-0.325	0.032	0.000

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The search strategy aimed at identifying the best quality and recent studies to estimate the effect of this risk factor. Three main databases were consulted: Scholar, Trid and Science Direct. In general, only recent (after 1990) journal studies and papers in the field of Engineering were initially considered. The iRAP toolkit and the CEDR website were consulted too without any interesting results. No "grey" literature was examined.

Database: TRID **Date:** 1st of April 2016

Limitations/ Exclusions:

- Published: 1990 to 2016
- Document source : ALL, Documents: Articles and papers, Subject area : ALL
- Language: English

Table 4 Literature search in TRID

search no.	search terms / operators / combined queries	hits
#1	Work zones	1887
#2	Work zones high duration	12
#3	Work zones small length	0
#4	Work zone insufficient signage	0

Database: Google Scholar **Date:** 1st of April 2016

Limitations/ Exclusions:

- Published: 1990 to current
- Document Type: ALL
- Sorted by relevance

Table 5 Literature search in Google Scholar

search no.	search terms / operators / combined queries	hits
#1	"Work zones"	10700
#2	"Work zones" AND "risk factor"	242
#3	"work zones" AND "risk factor" AND "small length"	4
#4	"work zones" AND "risk factor" AND "long duration"	8
#5	"work zones" AND "risk factor" AND "insufficient signage"	0

Database: ScienceDirect **Date:** 1st of April 2016

Limitations/ Exclusions:

- Search field: Abstract, title, keywords

- Published: 1990 to current
- Document Type: Journals Articles
- Subject Area: Engineering

Table 6 Literature search in ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	"work zones"	178
#2	AND "risk factor"	48
#3	AND "small work zones length" OR "high work zone duration" OR "insufficient signage"	40

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)
- Prioritizing Step D (Studies from Europe)

Results of Literature Search

Table 7 Overall literature search

Database	Hits
Google Scholar	1686
TRID	1899
ScienceDirect	266
Total number of studies to screen title	**3851**

Screening

After the total number of initially considered studies was identified (3851 studies), a screening was carried out. After title screening 64 relevant studies remain. Then an abstract screening was carried out and 29 studies considered relevant. Finally, a full-text screening took place and 8 relevant studies were coded.

Table 8 Overview of screening

Total number of studies to screen title	3851
Number of articles remaining after screening of the title = Total number of studies to screen abstract	64
Remaining studies after abstract screening	29
Total number of studies to screen full text	29

3.2 SUMMARY OF RESULTS

Table 9 Summary of results

Number	Author(s); Year;Country	Outcome indicator	Quantitative estimate	Effect on road safety

1	Khattak et al.; 2002; USA	Crash frequency[number of crashes]	Non-injury and injury crashes: beta coefficient=0.6718, st.error=0.0539	↑
			Non-injury crashes: beta coefficient=0.6112, st.error=0.1691	↑
			Injury crashes: beta coefficient=0.7842, st.error=0.0981	↑
2	Ozturk et al.;2013;USA	Crash frequency[number of crashes]	Total crashes: beta coefficient=0.477, st.error=0.133	↑
3	Ozturk et al.;2014;USA	Crash frequency[number of crashes]	Property damage and injury crashes: beta coefficient=0.5341, st.error=0.015	↑
			Property damage and injury crashes, daylight: beta coefficient=0.5750, st.error=0.017	↑
			Property damage and injury crashes, night: beta coefficient=0.4680, st.error=0.021	↑
			Property damage only crashes: beta coefficient=0.55, st.error=0.017	↑
			Injury crashes: beta coefficient=0.599, st.error=0.034	↑
4	Chen and Tarko;2012;USA	Crash frequency[number of crashes]	All crashes: beta coefficient=0.9467, t-statistic=10.1	↑
5	Chen and Tarko;2014;USA	Crash frequency[number of crashes]	All crashes: beta coefficient=0.8810, t-statistic=26.974	↑
6	Venugopal and Tarko;2000;USA	Crash frequency[number of crashes]	All crashes: beta coefficient=0.7601, t-statistic=4.8331	↑
			Fatal and injury crashes: beta coefficient=0.8531, t-statistic=0.2358	↑
			Property damage crashes: beta coefficient=0.9956, t-statistic=4.213	↑
7	Yang et al.; 2013; USA	Crash frequency[number of crashes]	Property damage crashes: beta coefficient=0.847, st.error=0.006	↑
			Injury crashes: beta coefficient=0.995, st. error=0.082	↑

8	Yang et al.; 2015; USA	Crash risk[probability of crash occurrence)	Beta coefficient=0.882, p-value=0.005	↑

3.3 LIST OF STUDIES

3.3.1 List of coded studies

A detailed list of studies coded is provided below:

1) Chen E., Tarko A. (2014). Modeling safety of highway work zones with random parameters and random effects models. Analytic methods in Accident Research, 1, 86-95.

2) Chen E., Tarko A. (2012). Analysis of workzone crash frequency with focus on police enforcement. In 91st Transportation Research Board Annual Meeting, Transportation Research Board of the National Academies, Washington, D.C., 2012.

3) Khattak A., Khattak A., Council F. (2002). Effects of work zone presence on injury and non-injury crashes. Accident Analysis and Prevention 34 (1), 19–29.

4) Ozturk O., Ozbay K., Yang H., Bartin B. (2013). Crash Frequency Modeling for Highway Construction Zones. In 92nd Transportation Research Board Annual Meeting, Transportation Research Board of the National Academies, Washington, D.C., 2013.

5) Ozturk O., Ozbay K., Yang H., Bartin B. (2014). Estimating the Impact of Work Zones on Highway Safety. In 93rd Transportation Research Board Annual Meeting, Transportation Research Board of the National Academies, Washington, D.C., 2014.

6) Venugopal S., Tarko A. (2000). Safety models for rural freeway work zones. Transportation Research Record: Journal of the Transportation Research Board, No. 1715, 1–9.

7) Yang H., Ozbay K., Ozturk O., Yildirimoglu M. (2013). Modeling work zone crash frequency by quantifying measurement errors in work zone length. Accident Analysis and Prevention, 55, 192– 201.

8) Yang H., Ozbay K., Xie K., Bartin B. (2015). Modeling Crash Risk of Highway Work Zones with Relatively Short Durations. Transportation Research Board's 94th 48 Annual Meeting, Washington, D.C., 2015.

3.3.2 Other references

1) Karlaftis M.G., Tarko, A. (1998). Heterogeneity considerations in accident modeling. Accident Analysis and Prevention 30 (4), 425–433.

2) Washington S.P., Karlaftis M.G., Mannering F.L. (2010). Statistical and econometric methods for transportation data analysis. Chapman & Hall/CRC.

Synopsis 12: Presence of workzones- Workzone duration

1 Summary

Theofilatos A., Papadimitriou E., Ziakopoulos A., Yannis G., Diamandouros K., Durso C.
September 2016

COLOUR CODE: GREY

Explanation: The presence of long duration of workzones was initially considered a risk factor as longer workzones are associated with more crashes. This was reported by almost all coded studies which show a consistent increase in the number of crashes and confirmed by the preliminary (uncorrected for publication bias) meta-analysis carried out. However, publication bias was detected and the corrected meta-analysis showed a non-significant effect.

KEYWORDS

Work zones; duration; crashes

1.1 ABSTRACT

Presence of long duration work zones can cause safety issues to drivers, because work zones are unfamiliar road environments for most road users, due to special arrangements. In general, however, work zone duration was found to have a non-significant impact on road safety. The vast majority of international literature investigates crash frequency, indicating that increased duration of works in road networks leads to an increased number of crashes at a 95% confidence level. However, the meta-analysis carried out, revealed a non-significant overall estimate of work zone duration after correcting for publication bias. Moreover, only one study was found to investigate crash risk (probability of crash occurrence vs non-crash occurrence), suggesting that work zone duration has no signigicant effect on crash risk.

1.2 BACKGROUND

1.2.1 How does work zone duration affect road safety?

Intuitively, it is expected that high duration of works on roads may increase risk of crashes. Presence of long duration work zones can cause safety issues to drivers, because work zones are unfamiliar road environments for most road users, due to special arrangements (lane closures, traffic disruptions, changes in road delineation and signage, presence of barriers, obstacles, workers etc.). Consequently, it is likely that they pose a greater threat to the safety of road users than regular road segments. Therefore, presence of such arrangements for long periods of time, can deteriorate road safety levels.

1.2.2 Definitions of workzone duration

This risk factor has a straightforward definition in international literature. It refers to the number of days that the work zone is operational and is defined as "work zone duration" and examined as numerical variable measured in days. However, a couple of studies measure it as the natural logarithm of days for modelling purposes.

1.2.3 Which safety outcomes are affected by work zone duration?

The literature search shows that the effect of work zone duration on road safety has been measured mainly on the basis of crash frequency (number of crashes occurred). Less frequently, it was found to be measured as crash risk (crash occurrence vs non-crash occurrence). It is noted that no studies concerning crash or injury severity were identified through the literature search.

1.2.4 How is the effect of work zone duration studied?

In international literature, crash data from police records are usually utilized to study the impact of work zone duration. Regarding the methods of analysis, the effect of workzone duration is usually examined by applying multivariate linear statistical models. When crash frequency is examined, the relationship between duration and number of crashes is investigated by applying fixed effects Negative binomial models. Probability of crash occurrence was investigated by applying rare-events logistic regression models.

1.3 OVERVIEW OF RESULTS

The initial examination of relevant studies consistently suggested that that longer duration work zones have increased number of crashes. Furthermore, when crash risk is examined (probability of crash occurrence vs non crash occurrence), there is no effect of work zone duration. All examined studies are based on data from 3 States of the US (Indiana, New Jersey and California). Moreover, little is known about various road users as the number of total crashes is investigated and transferability is not certain. Regarding the area type, usually highways are examined. One study (Khattak et al., 2002) investigates urban and non-urban roads.

All studies applied the same modeling approach with similar specification (fixed effects negative binomial models) and considered very similar control variables (environmental, traffic etc.). Therefore, after applying the appropriate transformations, it was attempted to apply a random effects meta-analysis for the effect of work zone duration on crash frequency. The results suggested a non-significant effect for a 95% level of confidence. Moreover, a meta-regression was applied in order to identify which study characteristics (moderator variables) affect the overall estimate. The results indicate that the year of the study and the study area are the core determinants of the overall estimate. More specifically, recent studies and studies on California State were found to provide higher estimates.

1.4 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality. Although all studies are methodologically correct, the statistical methods might be considered a bit obsolete. The only potential bias indicated is the fact the applied statistical methods and model specifications in these studies do not account for unobserved heterogeneity[1] that is possibly present, because they assume the effect of the explanatory variable (work zone duration) on the frequency of crashes is constrained to be the same for all observations (all work zone segments). Consequently, the resulting parameter estimates may be biased. Overall, this risk factor has not been extensively studied, although a relatively sufficient number of studies on crash frequency exists. However, there are no studies focusing on the effect of work zone duration on crash or injury severity. Moreover, they have all studies been conduted in US States and there is no specific focus on different road users. In conclusion, different modeling approaches are needed and data concerning more countries and different road users. Consequently, this risk factor needs further examination.

[1] For more details, the reader is encouraged to refer to Karlaftis and Tarko (1998) and Washington et al. (2010).

2 Scientific overview

2.1 LITERATURE REVIEW

Transportation network is frequently affected by the disruptions of the increasing number of work zones associated with construction, maintenance, and rehabilitation projects. This issue is particularly notable for critical freeways and arterials. There is strong evidence that work zones are a hazardous roadway environment to drivers that increases the risk of road crashes and injuries. The reduction of number and capacity of road lanes, the changes in road delineation and signage, the presence of workers, construction machinery, roadside construction barriers and other objects and obstacles, may create a core complex environment with increased conflicts that in turn leads to high risk conditions. Thus, the safe and efficient movement of drivers through work zones is a major concern to transportation engineers, road industry and researchers.

The literature search showed that there are a lot of studies examining road safety of workzones. However, there are very few studies using quantitative methods in order to acquire relationships between work zone characteristics and road safety indicators. In addition, some risk factors (e.g. work zone duration and length) have not adequately been explored, as many studies take into account behavioural and other geometrical parameters from police records regarding crashes in work zones.

Duration is one of the main risk factors associated with work zone characteristics. Since work zones are unfamiliar environments to road users, it is intuitive that presence of work zones for long time periods will cause more crashes. However, someone could argue that short durations of works in highways may cause a surprise to drivers and prevent drivers from adapting their driving behaviour. This risk factor has a straightforward definition in international literature. It is defined as "work zone duration" and examined as numerical variable measured in days. It is observed that crash data from police records are utilized to study the impact of work zone duration. Chen and Tarko (2014), argue that work zone information and data should be better reported in crash police records. Another issue mentioned by the authors is the limited data availability regarding work zone characteristics as detailed road cross-section data and traffic management plans are not readily available.

In general, duration of work zones seem to increase the number of crashes (Pal and Sinha, 1996). Khattak et al. (2002) quantified the effect of work zone duration on non-injury and injury crashes on the basis of California crash data for 1992 and 1993. The authors found that duration increases occurrence of both non-injury and injury crashes. Another similar study by Ozturk et al. (2013) used 2004-2010 crash data in work zones of New Jersey states and argued that increased l duration are associated with increased number of crashes. Venugopal and Tarko (2000) investigated the effect of work zone characteristics on the crash frequencies for different injury severity levels and found similar relationships across different injury categories. Therefore, the effect of work zone duration on road safety has been mainly measured on the basis of crash frequency (number of crashes occurred). Less frequently, it was found to be measured as crash risk (probability of crash occurrence vs non-crash occurrence), but it is not affected by work zone duration (Yang et al., 2015).

Concluding, there is relatively limited research on the topic and this may be mainly attributed to two reasons: a) the small available samples of crashes during the works (due to the usually short duration of work zones) and b) the small samples of relevant data after the end of the work zone (also due to the improvement of the safety level).

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

Five high quality studies were selected and coded. Four of the studies investigated crash frequency (Khattak et al., 2002; Ozturk et al., 2013; Pal and Sinha 1996; Venugopal and Tarko, 2000), while 1 study investigated the probability of crash occurrence (Yang et al., 2015). In order to examine the underlying relationships between work zone duration and outcome indicators, all studies deployed multivariable statistical models (fixed effects negative binomial), as a method of examining the topic and controlled for other geometrical characteristics, traffic flow, number of lanes and other crash related variables.

All 4 studies which investigate crash frequency, indicate a significant effect of duration on the number of crashes, regardless of the severity level (non-injury crashes, total crashes etc.) or the state (New Jersey, California, Indiana). In 2 of those studies (Khattak et al., 2002; Ozturk et al 2013) the unit of analysis was the natural logarithm of work zone duration in days. An interesting remark is that there is no distinction between road user groups as all road users of highways are considered (or no detailed information is provided).

The studies that investigated crash frequency utilized data from the US (mainly examining a different State in each study), applied the same statistical models (fixed effects negative binomial models) and found consistent results in general. The undertaken analysis methods are straightforward and might be now considered as obsolete, but the fact that most of studies were carried out before 2002 explains this. Clearly, there is room for further research on this topic on the basis of analytical methods.

It is therefore concluded that, as duration of work zones increases, there is an increase in the number of crash occurred. Yang et al. (2015) on the other hand, found that work zone duration has no effect on crash risk (crash probability), as the parameter work zone durations was not even retained in the final proposed statistical model as non-significant. Table 1 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 1 Description of coded studies

Author(s), Year	Sample and study design	Method of analysis	Unit of analysis	Outcome indicator	Main result
Khattak et al., 2002	2038 total crashes in 36 work zone sites in Indiana state, US, for the years 1992 and 1993.	Fixed effects negative binomial model	Natural logarithm of duration in days	Crash frequency (number of no injury, injury and total crashes)	Increased work zone duration leads to increased number of all types of crashes.
Ozturk et al., 2013	5382 total crashes in New Jersey State, US for the period 2004-2010.	Fixed effects negative binomial model	Natural logarithm of duration in days	Crash frequency (number of crashes)	Increased work zone duration leads to increased number of crashes.
Pal and Sinha, 1996	21 work zone sites using partial lane closures, 13 work zone sites using crossover, in Indiana State, US, for the period 1988-1992.	Fixed effects negative binomial model	Duration in days	Crash frequency (number of crashes)	Increased work zone duration leads to increased number of crashes.
Venugopal and Tarko, 2000	5025 total crashes in work zones in Indiana State, US, for the period 1993-1997.	Fixed effects negative binomial model	Duration in days	Crash frequency (number of no injury, injury and total crashes)	Increased work zone duration leads to increased number of all types of crashes.

Yang et al. 2015	466 work zones with 44 crashes in New Jersey state, US, for the year 2011.	Rare-events logistic regression	Duration in days	Crash risk (crash vs non-crash occurrence)	Non-significant effect.

2.3 ANALYSIS METHODS AND RESULTS

2.3.1 Introduction

A meta-analysis has been carried out in order to find the overall estimate of work zone duration on crash frequency. The reasons for this decision is that:

a) A minimum required number of studies is achieved (3)
b) Studies used the same model specifications (fixed effects negative binomial model)
c) The sampling frames were similar

Moreover, a meta-regression was applied in order to identify the study characteristics influencing the overall estimate.

2.3.2 Overall estimate for crash frequency

A random-effects meta-analysis was carried out, because there was considerable heterogeneity in coefficient estimates of work zone duration as indicated by I^2 and Q-test. The overall estimate of work zone duration (in days) was found to be 1.035 and the 95% confidence intervals were found to be 0.247 and 1.823 respectively as shown in the forest plot (Figure 1).

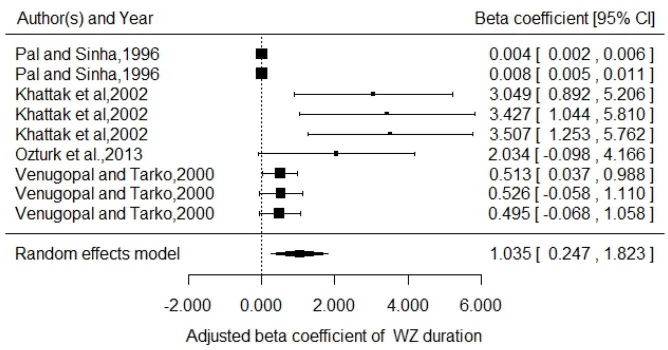

Figure 1 Forest plot of the effect of work zone duration (in days) on crash frequency (uncorrected estimate).

This effect was found to be 95% significant (p-value=0.01). However, after correcting for publication bias, an estimate of 0.1703 was produced, which was not significant.

Table 2 Initial and corrected random effects meta-analyses for work zone effects on crash frequency.

Variable	Unit	Effect	Estimate	Std. Error	p-value	95% CI
Duration	days	Uncorrected	1.035	0.4018	0.010	(0.247, 1.823)
Duration	days	Corrected	0.1703	0.5327	0.7492	(-0.874, 1.214)

2.3.3 Heterogeneity

The Q test is significant (Q = 43.6401, p-value < 0.0001) suggesting considerable heterogeneity among the true effects.

2.3.4 Publication Bias

A funnel plot was firstly produced in order to detect potential publication bias. The funnel plot is not symmetric suggesting that there is publication bias. Moreover, the regression test showed a t-value of 8.2413 (p-value <0.0001) confirming the existence of publication bias. The initial and the corrected for publication bias funnel plots are illustrated on Figures 2 and 3. A vertical solid line represents the overall effect, while the dots represents each effect of each study.

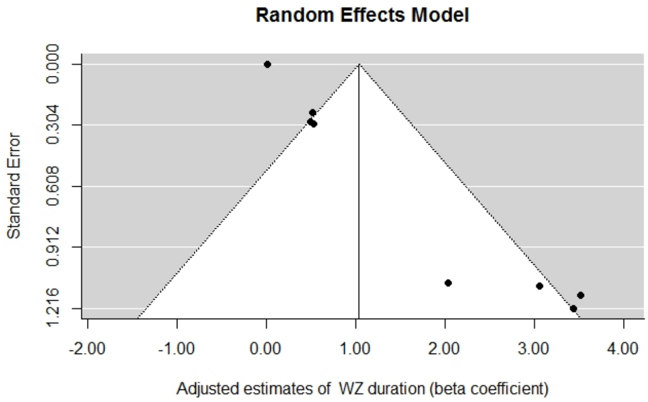

Figure 2 Initial Funnel Plot without correcting for publication bias.

Another method for testing for publication bias is to test whether the observed outcomes are related to their corresponding standard errors. However, due to the fact that only 3 studies exist, this test is not preferred. For that reason, a trim-and-fill method is applied. The results show that the estimated number of missing studies on the left side is 2. The corrected overall effect (13 estimates) was found to be 0.0001 (p-value=0.9988) showing a non-significant effect. The Q value is 68.4890 and is significant as previously (p-value < 0.001), suggesting again the presence of heterogeneity. Figure 3 that follows, illustrates the corrected funnel plot in order to account for publication bias.

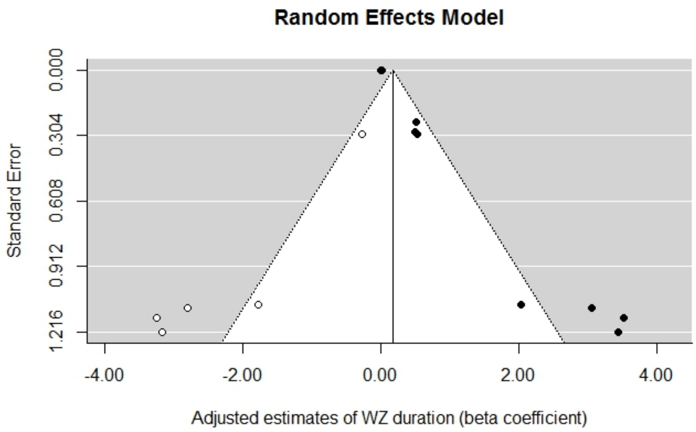

Figure 3 Adjusted Funnel Plot for Publication Bias

2.3.5 Meta-regression

In order to further explain the heterogeneity in the existing effects reported in the literature, a meta-regression analysis was carried out. Summary results are provided on Table 3.

Table 3 Initial and corrected random effects meta-analyses for work zone effects on crash frequency.

Moderator Variable	Estimate	Standard error	p-value

Constant term	-251.738	47.305	0.003
Year	0.126	0.024	0.003
Indiana state	-0.406	0.148	0.041
New Jersey state	-1.849	0.268	0.001
California state (reference category)	-	-	-

Results indicate that the main moderator variables (study characteristics) affecting the overall estimate of work zone duration are the year and the region (State) of study. More specifically, the sign of the beta coefficient of the year of the study, shows that more recent studies are more likely to report higher estimates. The estimates of work zone duration on crash frequencies in California (reference case) are higher than in Indiana and New Jersey. Consequently, researchers or policy makers may use with caution the initial uncorrected estimate, especially if their study setting is similar to that of more recent studies.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The search strategy aimed to identify the best quality and recent studies to estimate the effect of this risk factor. Three main databases were consulted: Google Scholar, Trid and Science Direct. In general, only recent (after 1990) journal studies and papers in the field of Engineering were initially considered. The iRAP toolkit and the CEDR website were consulted too without any interesting results. No "grey" literature was examined.

Database: TRID **Date:** 1st of April 2016

Limitations/ Exclusions:

- Published: 1990 to 2016
- Document source : ALL, Documents: Articles and papers, Subject area : ALL
- Language: English

Table 4 Literature search in TRID

search no.	search terms / operators / combined queries	hits
#1	Work zones	1887
#2	Work zones high duration	12
#3	Work zones small length	0
#4	Work zone insufficient signage	0

Database: Google Scholar **Date:** 1st of April 2016

Limitations/ Exclusions:

- Published: 1990 to current
- Document Type: ALL
- Sorted by relevance

Table 5 Literature search in Google Scholar

search no.	search terms / operators / combined queries	hits
#1	"Work zones"	10700
#2	"Work zones" AND "risk factor"	242
#3	"work zones" AND "risk factor" AND "small length"	4
#4	"work zones" AND "risk factor" AND "long duration"	8
#5	"work zones" AND "risk factor" AND "insufficient signage"	0

Database: ScienceDirect **Date:** 1st of April 2016

Limitations/ Exclusions:

- Search field: Abstract, title, keywords
- Published: 1990 to current
- Document Type: Journals Articles
- Subject Area: Engineering

Table 6 Literature search in ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	"work zones"	178
#2	AND "risk factor"	48
#3	AND "small work zones length" OR "high work zone duration" OR "insufficient signage"	40

Results of Literature Search

Table 7 Overall literature search

Database	Hits
Google Scholar	1686
TRID	1899
ScienceDirect	266
Total number of studies to screen title	**3851**

Screening

After the total number of initially considered studies was identified (3851 studies), a screening was carried out. After title screening 64 relevant studies remain. Then an abstract screening was carried out and 29 studies considered relevant. Finally, a full-text screening took place and five relevant studies were coded.

Table 8 Overview of screening

Total number of studies to screen title	3851
Number of articles remaining after screening of the title = Total number of studies to screen abstract	64
Remaining studies after abstract screening	29
Total number of studies to screen full text	29

3.2 SUMMARY OF RESULTS

Table 9 illustrates the summary of results.

Number	Author(s); Year;Country	Outcome indicator	Quantitative estimate	Effect on road safety
1	Khattak et al.; 2002; USA	Crash frequency[number of crashes]	Non-injury and injury crashes: beta coefficient=1.1149, st.error=0.0959	↑
			Non-injury crashes: beta coefficient=1.2317, st.error=0.1953	↑
			Injury crashes: beta coefficient=1.2549, st.error=0.1399	↑

2	Ozturk et al.;2013;USA	Crash frequency[number of crashes]	Total crashes: beta coefficient=0.71, st.error=0.084	↑
3	Pal and Sinha;1996; USA	Crash frequency[number of crashes]	For sites using partial lane closure: beta coefficient=0.0042, t-statistic=4.752	↑
			For sites using crossover:beta coefficient=0.0079, t-statistics=5.559	↑
4	Venugopal and Tarko;2000;USA	Crash frequency[number of crashes]	All crashes: beta coefficient=0.5126, p-value=0.0345	↑
			Fatal and injury crashes: beta coefficient=0.5263, p-value=0.0073	↑
			Property damage crashes: beta coefficient=0.4952, p-value=0.0847	↑
5	Yang et al.; 2015; USA	Crash risk[probability of crash occurrence)	Not retained in the final model	-

3.3 LIST OF STUDIES

3.3.1 List of coded studies

A detailed list of studies coded is provided below:

1) Khattak A., Khattak A., Council F. (2002). Effects of work zone presence on injury and non-injury crashes. Accident Analysis and Prevention 34 (1), 19–29.
2) Ozturk O., Ozbay K., Yang H., Bartin B. (2013). Crash Frequency Modeling for Highway Construction Zones. In 92nd Transportation Research Board Annual Meeting, Transportation Research Board of the National Academies, Washington, D.C., 2013.
3) Pal R., Sinha K. (1996). Analysis of crash rates at interstate work zones in Indiana. Transportation Research Record: Journal of the Transportation Research Board, No. 1529pp. 19–29.
4) Venugopal S., Tarko A. (2000). Safety models for rural freeway work zones. Transportation Research Record: Journal of the Transportation Research Board, No. 1715, 1–9.
5) Yang H., Ozbay K., Xie K., Bartin B. (2015). Modeling Crash Risk of Highway Work Zones with Relatively Short Durations. Transportation Research Board's 94th 48 Annual Meeting, Washington, D.C., 2015.

3.3.2 Other references

1) Karlaftis M.G., Tarko, A. (1998). Heterogeneity considerations in accident modeling. Accident Analysis and Prevention 30 (4), 425–433.
2) Washington S.P., Karlaftis M.G., Mannering F.L. (2010). Statistical and econometric methods for transportation data analysis. Chapman & Hall/CRC.

Synopsis 13: Alignment deficiencies- Low curve radius

1 Summary

C. Goldenbeld, G. Schermers & J.W.H. van Hendrik van Petegem (SWOV, sept. 2016)

1.1 COLOUR CODE: RED

Curve radius is a crash risk factor since there is a direct relationship between the radius of a horizontal curve and crashes and crash outcomes. The smaller the curve radius, the larger the risk for crashes. The radius of curve interacts with other design elements (horizontal alignment, vertical alignment, superelevation, side friction) to enable safe driving in the curve.

1.2 KEYWORDS

Curve radius, curvature, Crashes

1.3 ABSTRACT

Average crash rates are higher on horizontal curves than on straight sections of rural 2-lane highways. Radius or degree of curvature consistently tops the list of geometry variables that most significantly affect operating speeds and crash experience on horizontal curves. The crash rate increases with lower curve radii (tighter curves), with strong increase for radii < 200 metres. In general sharp curves in combination with long straight sections, sharp vertical sag or sharp crest curves, and a sequence of gentler curves are factors that increase risk in curves. For specific groups of drivers, such as motorcyclists and truck drivers, curves with low radii may be more risky than for other drivers and may require additional risk mitigating measures. The analysis of coded studies confirmed that curves with low radii have a higher crash risk. Moreover this analysis showed that crash modification functions for curve radius are very different for curve radii < 200 metres, with particular steep functions for Germany and USA. Based on USA rural highway studies, the analysis of coded studies found steeper crash modification factors for fatal/injury crashes than for Property Damage Only (PDO) crashes; it was also found that low curve radius is especially risky in interaction with vertical sag or crest curves, and that curve radius was the strongest predictor for motorcycle-to-barrier crashes.

1.4 BASIC CONCEPT OF CURVES

The *horizontal alignment* of a road comprises straight lines, circular curves (with a constant radius), and transition curves, whose radius changes regularly to allow for a gradual transfer between adjacent road segments with different curve radii (DaCoTa, 2012). Horizontal curves provide transitions between two straight sections of roadway (AASHTO, 2001).

1.5 THE RELATION BETWEEN CURVE RADIUS AND ROAD SAFETY

The design of roadway curves should be based on an appropriate relationship between design speed or operating speed and curvature and on their joint relationships with *superelevation* and *side friction* (AASHTO, 2001). In other words, simple curves have 4 main defining variables: radius, design speed or operating speed, side friction factor, superelevation (AASHTO, 2001).

When the curve is to tight, thus the radius of the curve to small, it means that the curve radius is not appropriate in combination with the other curve defining variables (design speed, superelevation and side friction factor) resulting in the risk on vehicles skidding or rolling over.

1.6 OVERVIEW OF METHODS AND RESULTS

The effect of curve radius has been studied in Europe and the USA. In recent studies the most used analysis strategy is to use generalized linear modelling, with the specification of a negative binomial (NB) error structure in order to develop a crash prediction model.

A meta-analysis of studies on curve radii was done by Elvik (2013). The literature search therefore concentrated on more recent research not covered by Elvik. 4 studies in period 2013-2016 were selected for further coding. The 4 studies differed in terms of outcome variables, length of crash period, variables included in the model, and statistical modelling procedure. Meta-analysis of these results was therefore not sensible nor advised.

The results can be briefly summarised as follows:

- 1 international study compared accident modification functions for eight countries and showed that functions were very different for radii < 200 metres with especially steep functions for Germany and USA (Elvik, 2013)
- 1 USA study showing that curve radius was the strongest predictor for motorcycle-barrier crashes (Gabauer & Li, 2015)
- 1 USA study demonstrating the increased crash risk as a result of the interaction between/ combination of low curve radius and sharp crest and sag vertical curves (Bauer & Harwood, 2013)
- 1 USA study that developed a Utah-specific crash model including curve radius. (Knecht et al., 2015).
- 1 USA study showing that crash modification factors were fatal and injury, PDO crashes) (Saleem & Persaud, 2016).

The results of all studies were consistent in showing that curves with lower radii are associated with higher crash rates. The accident modification functions and the parameter values for radius curve found in the USA studies cannot be automatically transferred to European situations. This is also clearly shown by Elvik (2013) who found that the accident modification function for curve radius was different between USA and Europe.

2 Scientific overview

2.1 LITERATURE STUDY

2.1.1 Basic concepts of horizontal curves

According to the laws of mechanics, when a vehicle travels on a curve it is forced outward by centrifugal force. On a superelevated highway, this force is resisted by the vehicle weight component parallel to the superelevated surface and side friction between the tyres and pavement. It is impractical to balance centrifugal force by superelevation alone, because for any given curve radius a certain superelevation rate is exactly correct for only one driving speed. At all other speeds there will be a side thrust either outward or inward, relative to the curve centre, which must be offset by side friction.

The purpose of superelevation or "banking" of curves is to counteract the centripetal acceleration produced as a vehicle rounds a curve. Superelevation is the inclination of the roadway toward the center of the curve. Friction between tyre and road surface is an important element in highway design. Friction values are used in the calculation of stopping sight distance and horizontal radius. The combined forces of superelevation and side friction help offset centripetal forces developed as the vehicle drives around a curve and help to keeps a vehicle from going off the road. The superelevation of the roadway must change gradually over a distance without noticeable reduction in speed or safety.

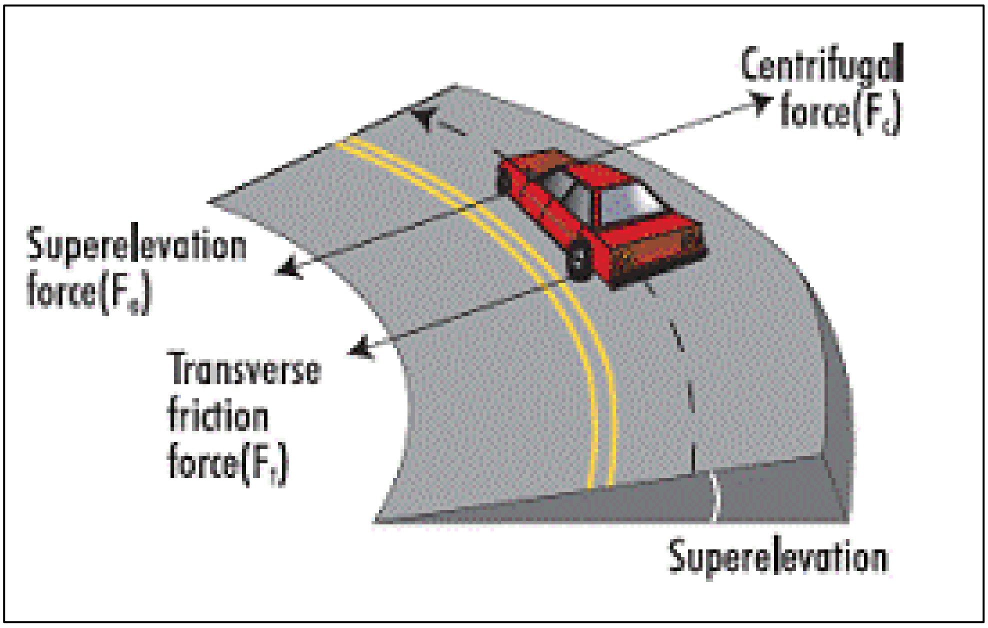

Figure 1. *Forces acting on a vehicle negotiating a superelevated curve*

2.1.2 Types of curves

There are different types of horizontal curves. A curve may *be simple*, *compound*, *reverse*, or *spiral*. Horizontal curves are curves used in horizontal planes to connect two straight sections. Simple curves are circular arcs connecting two straight sections. The simple curve is an arc of a circle.

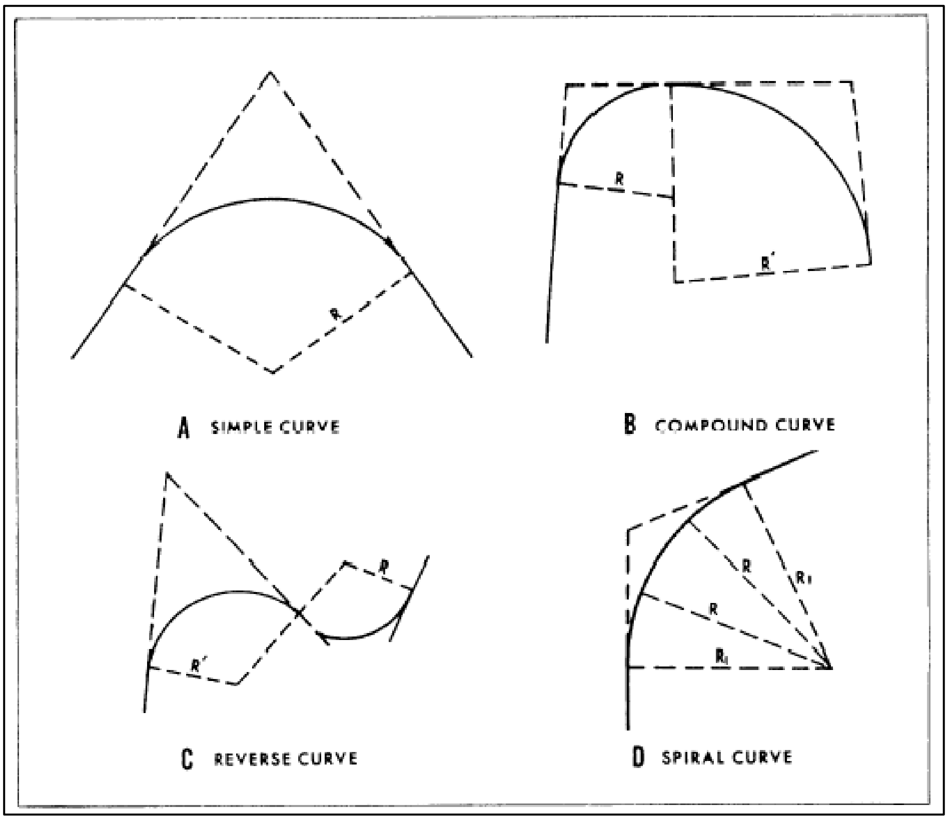

Figure 2. *Types of curves AASHTO (2001)*

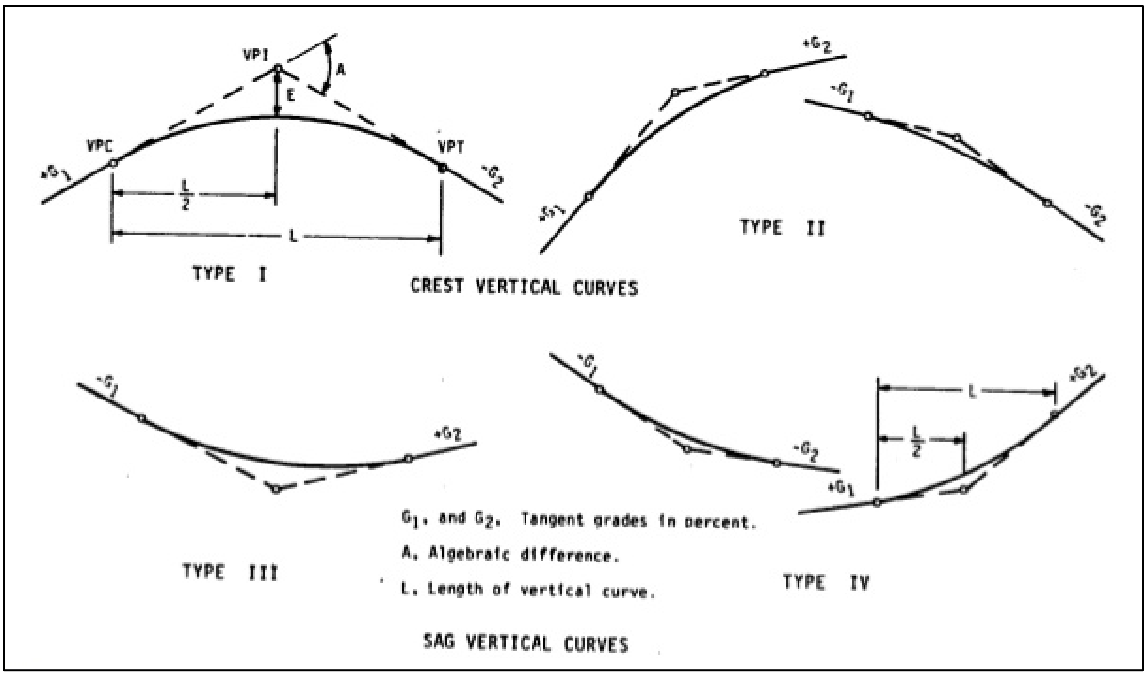

Figure 3. *Four types of vertical curves (AASHTO, 2001)*

2.1.3 How is curve radius related to crash risk?

The radius of a curve is a major defining feature of a curve next to other features such as superelevation, design speed and side friction factor. The curve or succession of curves is a major element of the (horizontal and vertical) alignment of a road. First we will briefly describe the relationship between horizontal alignment and road safety and curves and road safety and then we will discuss more specifically the relationship between curve radius and road safety.

In general the crash risk in horizontal curves is greater than on straight sections (tangents). According to one review (DaCoTa, 2012) the crash rate in curves is 1.5 to 4 times higher than in tangents (i.e. straight sections), the severity of crashes in curves is high (25 to 30% of all fatal crashes occur in curves) and a large proportion of crashes (60%) in horizontal curves are single-vehicle off-road crashes. Increased crash rates are observed on horizontal curves, because of the limited sight distance and the increased probability of skidding (DaCota, 2012). The majority of crashes on horizontal curves concern single vehicle run-off crashes and head-on collisions (DaCota, 2012).

The safety of a horizontal curve is partly determined by features internal to it (radius or degree of curve, super elevation, spiral, etc.) and partly by features external to it (density of curves upstream, length of the connecting tangent sections, sight distance, etc.) that influence driver expectation and curve approach speed (Hauer, 2000).

The radii of curves are one variable that affects the risk of lane-departure crashes on highways (Stein & Neuman, 2007). Other contributing factors may include the amount of superelevation, the surface friction of the pavement, and the horizontal and vertical alignments preceding the curve (Stein & Neuman, 2007). More specifically, horizontal curves of low radii lead to the following road safety problems (Hauer, 2000; DaCoTa, 2012; Stein & Neuman, 2007):

- In general research evidence shows that crash rate increases with lower curve radii, with strong increase for radii < 200 metres.
- The tendency of the crash rate to increase with lower curve radii is present not only on two-lane rural road but also on multilane roads and access controlled roads in urban and rural environments.
- A large central angle (i.e. the angle subtended at the centre of the circular curve) produces sharp horizontal curves that may have insufficient sight distance.
- If the transition from a tangent (i.e. straight) section to a circular curve is not achieved by a transition curve, there is greater risk of drivers making abrupt, risky movements in order to negotiate the curve.
- The presence of a single curve can be a risk factor, especially for low radii, i.e. a sharp curve located on a road with long preceding tangents, increases crash risk.
- A sharp (i.e. lower radius) curve after a long tangent or after a sequence of significantly more gentle (i.e. higher radius) curves can increase crash risk.
- Inadequate superelevation or pavement friction can contribute to vehicles skidding as they manoeuvre through a curve.

Curves can also present special road safety problems for specific types of road users. Motorcyclists are particularly at risk of collision on bends and curves, where acceleration and deceleration occur and the stability of the vehicle can be compromised (FEMA, 2012). Research has shown that riders are 15 times more likely to be killed than car occupants in this type of collision (FEMA, 2012).

Curves also present problems for large vehicle such as trucks. Horizontal curves can present special safety problems for trucks and other large vehicles. Because of their higher centre of gravity , large vehicles are more susceptible to overturning at curves (Stein & Neuman, 2007). Research confirms that such overturning can occur at speeds only slightly greater than the design speed of the curve (Stein & Neuman, 2007). Aesa and Abd El Halim (2006) calculated that an increase in the minimum radius of existing design guides (ranging from 5% to 27%) was required to compensate for the effects of reverse curvature and vertical alignment on truck rollover.

2.1.4 Which safety outcomes are affected by radius of curves?

The effects of curve radius on road safety have been studied in terms of a number of safety outcomes but predominantly in terms of crash frequency (number of crashes) and less so in terms of injury outcomes (number of injured persons). The most used outcome measures were total crashes.

2.1.5 How is the effect of radius of curves on crashes studied?

Nearly all studies investigated the effect of curve radius by developing Crash Prediction Models (APMs) through the application of statistical Generalised Linear Modelling (GLM) techniques. This synopsis focusses on one meta-analysis study in 2013 and studies 2013-2016. The coded studies were limited to the USA since these were the studies with the best data and method.

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 What is the relationship between crashes and radius of curves

5 studies were selected for coding on the basis of providing information on safety effects of curve radius. The focus was on the Elvik 2013 meta-analysis and studies after that 2013 review and meta-analysis. The 4 studies after Elvik (2013) all concerned safety effects of curve radius on 2 lane rural highways in USA. The 4 studies differed in several respects. 3 studies focused on all motorized vehicle crashes (Bauer & Harwood, 2013; Knecht et al., 2015; Saleem & Persaud, 2016) whereas one specifically dealt with motorcycle-to barrier crashes (Gabauaer & Li, 2015) Two studies analysed crashes according to injury levels (Bauer & Harwood, 2013; Saleem & Persaud, 2016), but 2 others used no injury distinction (Knecht et al, 2015; Gabauaer & Li, 2015). The 4 studies used different databases, with different lengths of crash periods, differing road characteristics, and all studies used unique analysis models. Below we describe the result of the 5 coded studies.

Elvik (2013) compared for 8 countries the accident modification functions that were developed to relate the radius of horizontal curves to their accident rate. The results of Elvik (2013) were best summarized in Figure 4 of his paper which is here reproduced as Figure 5.

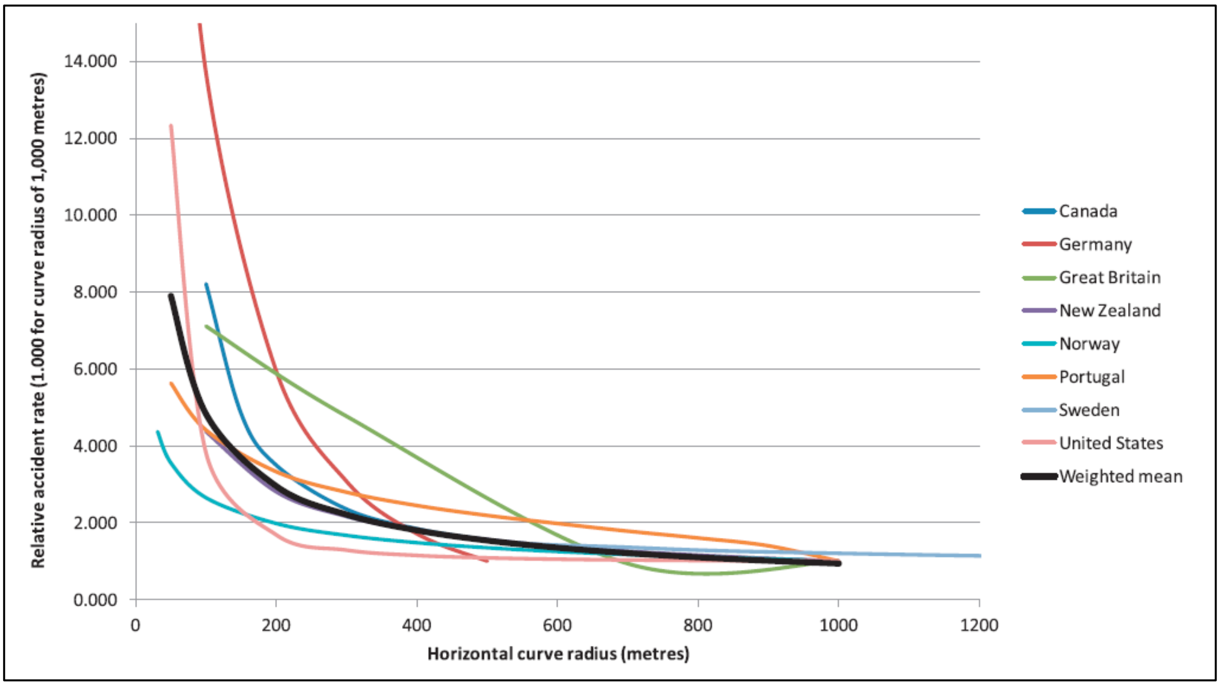

Figure 5. *Summary accident modification function and accident modification functions for horizontal curve radius in eight countries (taken form Elvik, 2013).*

Figure 5 shows that crash rates rapidly increase for curves smaller than 100-400 meters. It shows that the lower limit for the curve radius, from where the rapid increase sets in, differs for the different countries. Particularly steep functions were found for Germany and USA. The accident modification functions developed in Germany and the United States predict a larger increase in accident rates in sharp curves than the accident modification functions developed in the other countries. It is not known what the reasons for the difference are. And although it clearly shows how sharper curves relate to higher crash rates and that risk increases rapidly from some lower limit of the curve radius, it also suggests that international transferability is problematic for a correct estimating of crash rates contributed to a low curve radius.

In order to derive a summary accident function Elvik (2013) undertook 7 steps: estimating marginal gradient of relative accident rate; interpolating 100 metres steps datapoints for functions that increased in steps of 200 or 300 metres; estimating a simple arithmetic mean of the marginal gradient for each step of 100 m; estimating the variance of individual estimates around the arithmetic mean; assigning a weight inverse proportional to the variance associated with it; estimating a weighted marginal gradient and finally multiplying the weighted marginal gradients in order to form the summary accident modification function.

Figure 6 shows the summary accident modification function estimated by Elvik.

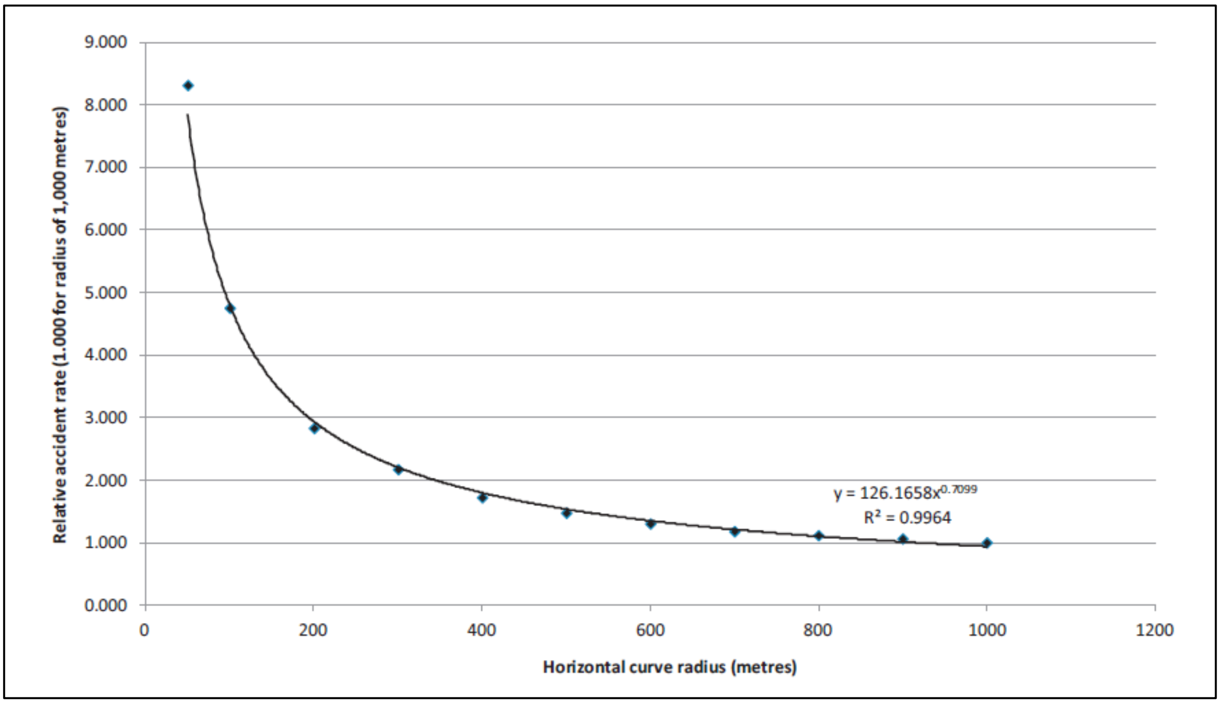

Figure 6. *Summary accident modification function for horizontal curve radius–data points weighted in inverse proportion to residual variance (taken from Elvik, 2013).*

The summary accident modification function is located in the middle of the accident modification functions developed in the eight countries and can, in that sense, be interpreted as an average of the functions developed in each country.

The graph depicting the summary accident modification function for horizontal curve radius closely fits a power function. The function is: Relative accident rate = $127.1658X^{-0.7099}$, where X is curve radius in metres (Elvik, 2013)

Bauer and Harwood (2015) have undertaken research to quantify the safety effects of combinations of horizontal curves and vertical curves for two-lane rural roads. These researchers conclude the following:
- short, sharp horizontal curves are associated with higher crash frequencies
- for type 1 crest curves, curve radius interacts with vertical grade difference in the sense that short horizontal curves combined with sharp crest vertical curves are associated with higher crash frequencies
- for type 1 sag curves, curve radius interacts with vertical grade difference in the sense that short horizontal curves at sharp sag vertical curves are associated with higher crash frequencies
- for type 2 sag curve, curve radius interacts with vertical grade difference so that short horizontal curves at sharp sag vertical curves are associated with higher crash frequencies (PDO model)

The Bauer and Harwood model had the annual number of crashes as dependent variable and AADT, curve radius, curve length and shoulder width as independent (predictor) variables.

Bauer & Harwood compared the crash modification factors for fatal and injury crashes and PDO crashes in their study with the general factors as described in the AASHTO Highway Safety Manual. These crash modification factors are depicted in Figure 3 is an analogous plot, where the length of horizontal curve and percent grade were kept constant, while the radius of the horizontal curve varied.

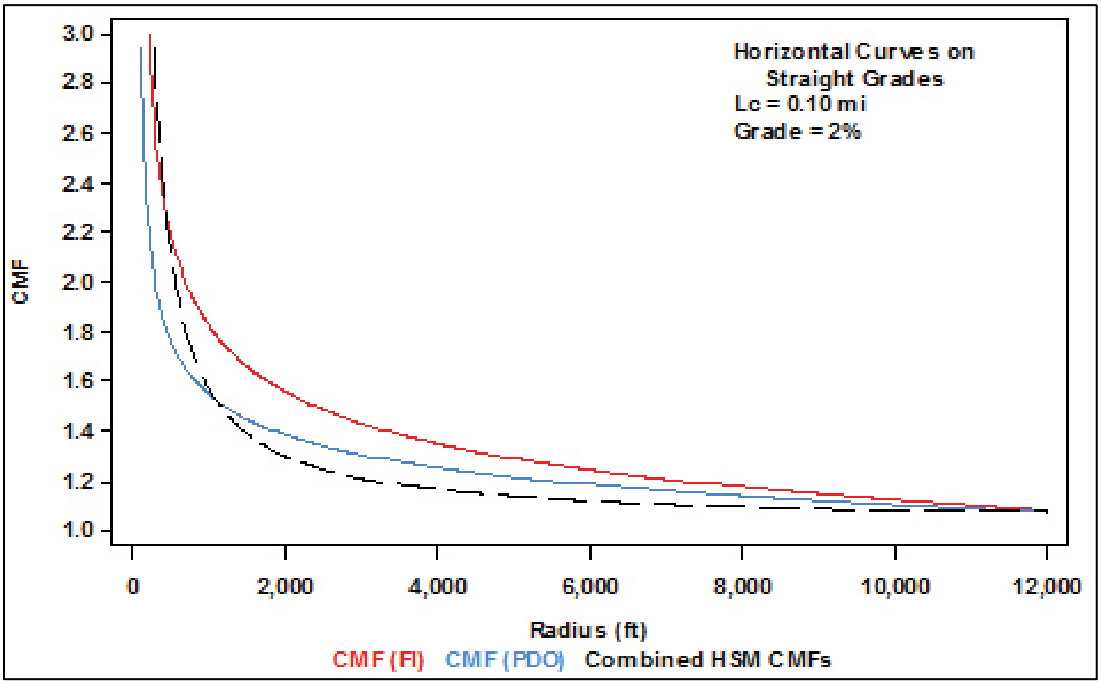

Figure 4. *Comparison of CMFs developed in Bauer and Harwood to the combined AASHTO HSM CMFs for horizontal curves and grades for fixed percent grade and varying radii* (*Bauer & Harwood, 2013).*

Figure 4 shows that the CMF for FI crashes developed in the Harwood & Bauer study is consistently larger than the CMF for PDO crashes developed in the study. According to the authors, this represents an advance in knowledge compared to the AASHTO HSM, which treated the CMFs as equal for all severity levels. The figure also show that the new CMFs are generally larger than the combined HSM CMFs, except that the new CMF for PDO crashes is smaller than the existing CMFs for horizontal curves with short radii.

Gabauer and Li (2014) studied the influence of horizontally curved roadway section characteristics on motorcycle-to-barrier crashes. Their data included 4915 horizontal curved roadway sections with 252 of these sections experiencing 329 motorcycle-to-barrier crashes between 2002 and 2011. The researchers used a negative binomial regression to predict motorcycle-to-barrier crash frequency using horizontal curvature and other roadway characteristics. They found that curve radius was the strongest predictor of crash frequency. More specifically they found that curves with curve radius of f 820 feet (250 meter) or less increased the crash frequency rate by a factor of 10 compared to curves not meeting this criterion. Curves with radius less than 500 feet were found to be more than 40 times more likely to experience a motorcycle-to-barrier crash than a curve with radius in excess of 2800 feet.

Knecht et al. (2015) developed crash prediction models for curved segments of rural two-lane two-way highways in the state of 2 Utah. The research effort included the calibration of the predictive model from the Highway Safety Manual (HSM) and the development of Utah-specific models with the use of negative binomial regression. For this research, two sample periods were used: a three-year period from 2010 to 2012 and a five-year period from 2008 to 2012. The independent variables used for negative binomial regression included the same set of variables used in the HSM predictive model along with other variables such as speed limit and truck traffic. The significant variables were found to be average annual daily traffic, segment length, total truck percentage, and curve radius.

Saleem and Persaud (2016) used a database of over 11,200 km (7,000 mi) of data 148 including roadway inventory, traffic volumes, crashes and curve/grade information. They selected data based on the following criteria: 1. Roadway type should be rural 2-lane highways; 2. Curves should be on grades of 3% or less (absolute) grade to eliminate the confounding 154 effects of harsh grade; 3. Minimum curve radius should be 30.5 m (100 ft.); 4. Maximum curve radius should be 3493 m (11460 ft.) 5. Posted Speed on the curve section should be between 50 – 60 mi./hr (~80 - 100 km/hr). Using these guidelines a total of 440 curves were selected. Consistent with state-of-the-art methods, generalized linear modelling, with the specification of a negative binomial (NB) error structure, was used to develop the crash prediction models.

2.3 ANALYSIS METHODS AND RESULTS

2.3.1 Introduction

The estimates in the 5 coded studies were subject to different statistical models with different sets of dependent and independent variables. Therefore the estimates are not directly comparable. Therefore the results do not lend themselves for meta-analysis.

The effects of curve radius can be summarised as follows:

- all studies show reduced crash rates for larger curve radii
- 1 study comparing crash modification function for horizontal curve radius in 8 countries finds that Germany and USA have divergent functions (Elvik, 2013)
- 1 study showing that low curve radii combined with sharp sag or crest type 1 vertical curves are especially risky (Bauer & Harwood, 2013)
- 1 study showing that curve radius was the strongest predictor of motorcycle-to-barrier crashes and that curves with curve radius of f 820 feet (250 meter) or less increased the crash frequency rate by a factor of 10 compared to curves not meeting this criterion (Gabauer & Li, 2015)
- 2 studies showing that radius curve had a larger coefficient estimate for fatal and injury crashes than for PDO crashes (Bauer & Harwood, 2013; Knecht et al., 2015)
- 1 study showing that annual daily traffic, segment length, total truck percentage, and curve radius provided a reasonably accurate estimate of predicted crashes for curved segments of rural two-lane two-way highways in Utah (Knecht et al., 2015)

Table 2 presents an overview of the main features of coded studies (sample, method, outcome indicator and results).

Table 2. Description of coded studies

Author, Year	Sample and study design	Method of analysis	Outcome indicator	Main result
Elvik 2013	International comparison of mathematical functions (crash modification functions) in 8 countries that have been developed to relate the radius of horizontal curves to their crash rate.	Meta-analysis	Crash rates	The relationship between horizontal curve radius and relative crash rate varies considerably between these countries. The values of relative crash rate for Canada and New Zealand are fairly close, but diverge for curves with a radius of 200 m or less. The functions for different countries also differ in terms of the range of curve radii they apply to. The summary crash function for curve radius was: Relative crash rate = $127.1658X^{-0.7099}$, where X is curve radius in metres
Bauer 2015	Study on the effects of the horizontal and vertical alignment on road safety. The results include several	Of the 6,944 mi of roadway in the entire Washington HSIS database, 4,785 mi (69 percent) are on rural two-lane highways. Of these, 3,457 miles were used for analysis. Of	Fatal and injury crashes per Mile per Year, & PDO crashes per	(a) Models for *horizontal curves on straight grades* indicate that crash frequency increases with decreasing horizontal curve radius, decreasing horizontal curve length, and increasing percent grade. The interaction term (curve radius x curve

Author, Year	Sample and study design	Method of analysis	Outcome indicator	Main result
	CPMs and CMFs on different combi-nations of horizontal curves , grades and vertical curve types	these were 985.0 miles for rural two-lane highways. The safety effects of horizontal curve and grade combinations were estimated based on a cross-sectional analysis using a generalized linear model approach assuming a negative binomial (NB) distribution of crash counts and an exponential model using the combined crash data from all 6 years and selected roadway geometrics. The parameters considered in each model may include the following: - Average annual daily traffic (AADT) (averaged across all 6 years). - Segment length. - Horizontal curve radius. - Absolute value of percent grade. - Horizontal curve length. - Vertical curve length. - Algebraic difference between the initial and final grades (A). - Measure of the sharpness of vertical curvature (K). - Relevant interactions of selected parameters.	mile per year	length) shows that short sharp horizontal curves are associated with higher crash frequencies. (b) Models for *horizontal curves at type 1 crest vertical curves* include a main effect for AADT and an interaction between horizontal curve radius and the difference between initial and final grade. The models indicate that crash frequency increases with decreasing horizontal curve radius and increases with increasing grade difference. The interaction term shows that short horizontal curves at sharp crest vertical curves are associated with higher crash frequencies. (c)Models for *horizontal curves at type 1 sag vertical curve*s indicate that crash frequency increases with decreasing K, decreasing horizontal curve radius, and increasing grade difference. The interaction term shows that short horizontal curves at sharp sag vertical curves are associated with higher crash frequencies. Models for *horizontal curves at type 2 crest vertical curves* indicate include two main effects: a main effect for AADT and a main effect for horizontal curve radius. The models indicate that crash frequency increases with decreasing horizontal curve radius. Models for *horizontal curves at type 2 sag vertical curves* differed by sverity level. The FI crash prediction model includes only two main effects: a main effect for AADT and a main effect for horizontal curve radius. This model indicates that FI crash frequency increases with decreasing horizontal curve radius. The PDO crash prediction model includes a main effect for AADT, an interaction between horizontal curve radius, and the difference between G1 and G2.
Gabauer 2015	The study aimed to identify risk factors on motorcycle barrier crashes at curves	Roadway and crash data from the Washington HSIS database was used for the analysis. Additional data on the presence of barriers at curves was gathered using roadway imagery from Google. The database contain-ned 13357 curve segments of which 5380 with a barrier. The effects of road design parameters were ana-lysed by developing loglinear regres-sion models with a Negative Binomial distribution. The final model includes the following predictors: ln curve radius (feet) , ln AADT, ln curve length (feet), non-isolated curve indicator, rural area indicator.	The dependent variable was the number of motor-cycle barrier crashes at curves with a barrier present.	The model showed that smaller curve radii correlate with an increase in crashes. The parameter estimates of the final model were highly significant. The strongest predictor of crash frequency was found to be curve radius. Other statistically significant predictors were curve length, traffic volume and the location of adjacent curves. Regrettably, no analysis of co-linearity was reported.
Knecht 2015	Study aimed at developing Utah specific crash pre-diction models for curved segments and calibration factors for CPMs from the Highway Safety Manual. Utah specific CPMs were developed using the complete dataset of 1495	Information about curves was obtained with the help of LiDAR data. 1495 sample curves were obtained from the UDOT data-base. The complete set was sampled into three sets of curves, for which separate calibration factors were deve-loped to check if model results would differ or not for different sets of curved segments. Two crash samples were determined. A 3 year sample from 2010-2012 and a 5 year	The number of crashes on curved segments of rural two-lane two-way highways in the state of Utah.	Both models indicated an increase in crashes for a decrease in curve radius.

Author, Year	Sample and study design	Method of analysis	Outcome indicator	Main result
	curves.	sample from 2008-2012. The final models for both the 3 year and 5 year crash sample set had the following predictors: Analysis length, vehicle count, truck %, ln radius. Data were analyses with negative binomial regression.		
Saleem 2016	The study develops/ presents CPMs for curve sections of rural undivided highways and CMFs for curve flattening based on these cpms.	The following road types were included: rural 2-lane highways; curves on grades of 3% or less (absolute) grade to eliminate the confounding effects of harsh grade; minimum curve radius 30.5 m (100 ft.) - maximum curve radius 3493 m (11460 ft.) and posted Speed on the curve section should be between 50 – 60 mi./hr (~80 - 100 km/hr) The functional form for the CPMs was based on earlier research by Zegeer. The predictors of the CPM were the AADT, length, curve radius, shoulder width and grade. The models were developed with Generalized Linear Modeling with a Negative Binomial-distribution.	Total crashes, fatal and injury crashes and property damage crashes only.	The results show that smaller curve radii correlates with more crashes. Regrettably no information is given about the safety zone or presence of barriers and no information on co-linearity analysis. .

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature search aimed at identifying the highest quality and most recent studies for quantifying the relationship between curve radius and crash occurrence (number of crashes) and crash severity. Therefore the document search strategy was primarily aimed at studies undertaken in Europe and published in recognized scientific journals and publications. Older studies and/or studies from other parts of the world but with the provison that these were published in recognized scientific publications are also considered but with lower priority. The Scopus and TRID databases were searched in the formal literature search. All searches were filtered on English results only. The literature search was done in 2016.

To select papers relating to road safety in Scopus, the following query was used: ((road and casualt*) or (road and injur*) or (road and accident*) or (road and crash*) or (traffic and injur*) or (traffic and casualt*) or (traffic and accident*) or (traffic and crash*)).

To select papers relating to road safety in TRID, the following query is used: (collision* or crash* or accident* or injur* or casualt*) AND (traffic or road).[1]

The aforementioned queries were combined with a query to select papers relating to the risk factor low curve radius: ((curve* and radius) or (curve* and radii) or curvature)
These queries were combined in Scopus and TRID to search for literature about the risk factor frequent curves. To distinguish literature from Europe and Worldwide, the results were loaded into Mendeley, where the following query was used to identify literature from Europe: (Italy or Ireland or Hungary or Greece or Germany or France or Finland or Estonia or Denmark or Czech or Cyprus or Croatia or Bulgaria or Belgium or Austria or Scotland or England or Britain or United Kingdom or Sweden or Spain or Slovenia or Slovakia or Romania or Portugal or Poland or Netherlands or Malta or Luxembourg or Lithuania or Latvia).

The search results based on the described search strategy is presented in table3.

Table 2 Literature search results

search no.	Region	Database	hits
#1	Europe	Scopus	47
#2	Europe	TRID	99
#3	Worldwide	Scopus	373
#4	Worldwide	TRID	805

[1] The difference in the queries is due to differences in restrictions to the query length between the two sources.

Following the initial selection of relevant publications, a secondary selection of publications was made in Mendeley, sorting the initial publications on year and source. Only publications from trusted sources and most recent publications after 2013 were selected, since a meta-analysis from 2013 was available. From this selection all abstracts were reviewed on relevance. From reviewing the abstracts a total of 16 publications were selected as the most promising. For 4 of these the full text version could not be retrieved and these were not considered further. The remaining 12 publications were reviewed and the 5 most relevant studies were coded including the meta-analysis .

3.2 LIST OF STUDIES

3.2.1 Coded studies

This paragraph contains a list of the coded studies.
A list of studies considered (and of which the first 5 were selected for coding) are listed below:

Bauer, K.M., & Harwood, D.W. (2013).*Safety Effects of Horizontal Curve and Grade Combinations on Rural Two-Lane Highways*. Report No. FHWA-HRT-13-077, Federal Highway Administration, Washington, DC.

Elvik, R. (2013). International transferability of crash modification functions for horizontal curves. *Crash Analysis & Prevention*, *59*, 487– 496

Gabauer, D.J., & Li, X. (2015). Influence of horizontally curved roadway section characteristics on motorcycle-to-barrier crash frequency. *Crash Analysis & Prevention*, *77*, 105–112.

Knecht, K.S., Saito, M., & Schultz, G.G.(2015). Crash prediction modeling for curved segments of 1 rural two-lane two-way highways in Utah. Submitted November 12 2015 for publication in Journal of Transportation Research Board.

Saleem, T. & Persaud, B. (2016). Another Look at the Safety Effects of Horizontal Curvature on 1 Rural Two-Lane Highways. The Transportation Research Board (TRB) 95th Annual Meeting,. Paper #16-6347. Transportation Research Board, Washington D.C..

3.2.2 Selected not coded references

Wang, Chao, Mohammed A. Quddus, and Stephen G. Ison. 2013. "The Effect of Traffic and Road Characteristics on Road Safety: A Review and Future Research Direction." *Safety Science* 57:264–75. Retrieved January 20, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84876312024&partnerID=tZOtx3y1).

Khan, Ghazan, Andrea Bill, Madhav Chitturi, and David Noyce. 2013. "Safety Evaluation of Horizontal Curves on Rural Undivided Roads." *Transportation Research Record: Journal of the Transportation Research Board* 2386(2386):147–57. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84897141872&partnerID=tZOtx3y1).

de Oña, Juan, Laura Garach, Francisco Calvo, and Teresa García-Muñoz. 2014. "Relationship between Predicted Speed Reduction on Horizontal Curves and Safety on Two-Lane Rural Roads in Spain." *Journal of Transportation Engineering* 140(3):Content ID 04013015. Retrieved (http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000624).

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April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84896302191&partnerID=tZOtx3y1).

Calvi, Alessandro. 2015. "A Study on Driving Performance Along Horizontal Curves of Rural Roads." *Journal of Transportation Safety & Security* 7(3):243–67. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84919629011&partnerID=40&md5=2dec1b7fc1e7649619e11f9c6831c840).

Saito, Mitsuru, Casey Knecht S, Grant Schultz G, and Aaron Cook A. 2015. *Crash Prediction Modeling for Curved Segments of Rural Two-Lane Two-Way Highways in Utah*. Retrieved (http://www.udot.utah.gov/main/uconowner.gf?n=26397103967317288).

Shafabakhsh, Gholamali and Yousef Sajed. 2015. "New Achievement for Prediction of Highway Accidents." *Engineering Journal* 19(1):139–51. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84922546821&partnerID=tZOtx3y1).

Donnell, Eric, Jonathan Wood, Scott Himes, and Darren Torbic. 2016. "Use of Side Friction in Horizontal Curve Design: A Margin of Safety Assessment." P. 21p in. Retrieved (https://trid.trb.org/view/1393917).

Colonna, Pasquale, Paolo Intini, Nicola Berloco, Antonio Perruccio, and Vittorio Ranieri. 2016. "Repeated Measurements of Lateral Position and Speed at Horizontal Curves on Very-Low-Volume Rural Road." P. 19p in. Retrieved (https://trid.trb.org/view/1393273).

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Pratt P, Michael and Srinivas Geedipally R. 2016. "Developing a Framework for Evaluating and Selecting Curve Safety Treatments." P. 18p in. Retrieved (http://docs.trb.org/prp/16-5801.pdf).

Gabauer, Douglas J. 2016. "Characterization of Roadway Geometry Associated with Motorcycle Crashes into Longitudinal Barriers." *Journal of Transportation Safety & Security* 8(1):75–96. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84949008574&partnerID=40&md5=0d0b799e6003e4577170d3870796cc7c).

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Synopsis 14: Alignment deficiencies - Absence of transition curves

1 Summary

C. Goldenbeld, G. Schermers, J.W.H. van Petegem. (SWOV, Sept. 2016)

1.1 COLOUR CODE: YELLOW

Although there may be a significant relationship between absence of transition curve and risk, the relationship is dependent upon various external factors, including type of terrain (level, rolling, mountainous), road width and Average Daily Travel (ADT). Relatively speaking, absence of transition curves is a much smaller risk factor than curve radius.

1.2 KEYWORDS

compound curve, spiral curve, transition curve, crashes, driver speed, operating speed, driver performance, centrifugal force, lateral acceleration

1.3 ABSTRACT

Transition curves are defined as the transition between a tangent and a circular curve. In a transition curve, the curve radius is not constant but gradually changes. These curves are often designed as clothoids (i.e. curves where the radius of curvature decreases linearly as a function of the arc length). Theoretically, a curve transition should improve safety because it gradually leads the driver into a natural safe path on the circular curve and it provides a space for superelevation to gradually change , thus minimizing excess side friction forces. The analysis of coded studies reveals that curved roads with transition curves are associated with improved driving performance and lower crash risk. Studies have shown a significant relationship between the absence of transition curve and risk, but this relationship is dependent upon various external factors including type of terrain (level, rolling, mountainous), road width, and ADT. There is an apparent interaction between the landscape and road design elements in curves and the application of transition curves strengthens these interactions and results in improved safety. However, the influence of transition curves on crashes is far less than the radius of the curve.

1.4 BACKGROUND

In section 1.3.1 we provide some definitions of basic concepts. Types of curves are described in section 1.3.2. In sections 1.3.3 we discuss how absence of a transition curve may influence road safety.

1.4.1 Curves and curve design

Horizontal curves provide transitions between two tangent lengths of roadway (AASHTO, 2001). The design of roadway curves should be based on an appropriate relationship between design speed and curvature and on their joint relationships with *super-elevation* and *side friction* (AASHTO, 2001). In terms of curve design, simple curves have 4 main defining features, namely radius, design speed or operational speed, side friction factor, and super-elevation (AASHTO, 2001). For details the reader is referred to Aashto 2001 (Green Book on highway design), 2011, HSM, Piarc safety design manual, etc.

Horizontal curves are curves used in horizontal planes to connect two straight tangent sections. There are different types of horizontal curves. A curve may *be simple*, *compound*, *reverse*, or *spiral (Aashto, 2011)*. This synopsis deals with transition curves which are curves or *Spirals* used to overcome the abrupt change in curvature and super-elevation that occurs between tangent and circular curve.

In curve design there are 3 possibilities for a transition (Council, 1998; see also Figure 1):
1. no transition section, where the tangent abuts the horizontal curve and the driver makes his or her own transition path;
2. a compound curve transition, where a short section of less sharp curve is placed between the tangent and the primary curve; and
3. a spiral transition, which begins as a tangent and ends with the same degree of curvature (sharpness) as the curve.

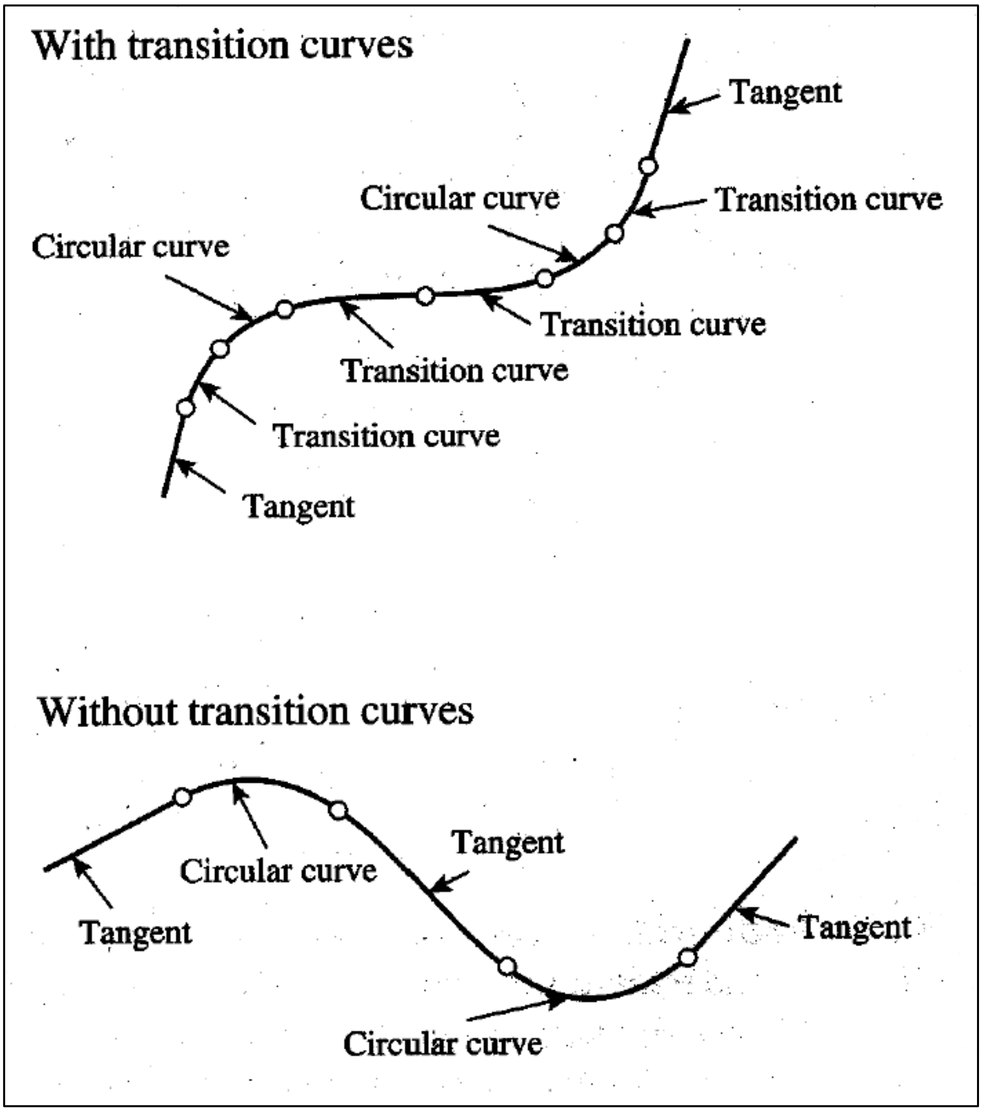

Figure 3. *Curves with and without transition curves.*

1.4.2 Definition of a transition curve

Transition curves (clothoids) are defined as a transition from a tangent (i.e. straight) section to a circular curve (i.e. the point where the radius of curvature reaches its minimum) (DaCota, 2012). In a transition curve, the road will gradually curve more and more. The international AASHTO/IRC design standards recommend that a transition curve in horizontal curves, should be designed as a clothoid. A clothoid is a curve where the radius of curvature decreases linearly as a function of the arc length. When driving in this type of curve, the driver will follow the curve by turning the wheel at a constant rate in the direction of the curve. Consequently, the need for abrupt movements, in order to negotiate the curve, is eliminated (DaCoTa, 2012).

1.4.3 How does the absence of transition curves affect road safety?

This synopsis focusses on 3 studies in USA and 1 in Iran, 3 studies on accidents and 1 study on simulated driving outcomes. The 3 accident studies investigated the effect of absence of transition curve by developing Accident Prediction Models (APMs).

The results can be briefly summarised as follows:
- 1 USA study showing that absence of spiral curves on rural 2 lane highways was associated with an average 5% increase in crashes (Zegeer et al., 1991)
- 1 USA study showing that the effects spiral curves on road safety can be both positive or negative and depend upon degree of curve, type of terrain, road width, and ADT (Council, 1998)
- 1 USA study showing that absence of spiral curve led to worse curve-related driving performance in a simulated environment (Zakowska, 2009)
- 1 Iran study showing that length of spiral curve was positively associated with crash decrease on 2-lane highways in Iran, however not tested for statistical significance (Aram, 2010)

The results of the coded studies were consistent in showing that absence of transition curves on a flat terrain and sharp curves are associated with worse driving performance and larger accident rates.
From the literature review some contradictory findings did rise, where findings indicated that spiral curves might relate to an increase in crashes (Tom, 1995; Council, 1998) and increase in driving speed through the curve (Helmers & Törnros, 2006; Imberg & Palmberg, 2015). However, the increase in crashes on curves with spirals was believed to be caused by insufficient sight distances, which might cause driver to only see the beginning of the curve and as a result underestimate its sharpness (Council, 1998). Also, although driver speed were found to increase in some instances with spiral curves present, the lateral acceleration rates did not seem to be affected in most cases (Helmers & Törnros, 2006; Imberg & Palmberg, 2015). An explanation would be that the spiral improved the trajectory and/or resulted in less steering corrections, which both would reduce the lateral acceleration rates and negate the increased speed.

1.4.4 Which safety outcomes are affected by absence of transition curve?

The effects of absence of transition curve on road safety have been studied in terms of a number of safety outcomes but predominantly in terms of crash frequency (number of crashes) and less so in terms of injury outcomes (number of injured persons). The most used outcome measures were total crashes.

1.4.5 How is the effect of absence of transition curves on crashes studied?

The effect of the risk factor on crashes is studied with cross section study designs and regression analysis with crashes or crash rates as the dependent. Other studies focus on the relation between driver performance and driver behaviour and curve design by means of a simulator study and naturalistic driving study.

1.5 NOTES ON ANALYSIS METHODS

The effect of absence of transition curve has been studied most often in USA. Of the 4 studies describing the relationship between transition curves and crashes, 3 are in USA and 1 in Iran; all three use different statistical models (linear accident rate model, linear logistic, Poisson regression) correcting for different possible confounders.

2 Scientific overview

2.1 LITERATURE REVIEW

Radius or degree of curvature consistently tops the list of geometry variables that most significantly affect operating speeds and crash experience on horizontal curves (Aram, 2010). The presence of transition curves belongs to a group of other geometric variables, including length of curve, defection angle, superelevation rate, and the location of a curve relative to other horizontal curves, for which lesser or less consistent effects have been found (Aram, 2010).

Theoretically, a curve transition section is meant to serve two safety-related functions. Firstly, it should provide and "direct" the driver into a safe path while changing the steering wheel position from one relatively fixed position (on the tangent) to a second fixed position (on the circular curve) (Council, 1998; AASHTO, 2011). Secondly, it should provide space for superelevation to change from the normal crown of the tangent to the full super elevation required by the circular curve, thus minimising excess side friction forces (Council, 1998; AASHTO, 2011).

Effect on crashes

Zegeer et al. (1991) showed that the presence of a spiral reduced total crashes by two to nine percent, depending on degree of curve and central angle. In contrast, a study by Tom (1995) in California compared crash severity and rates on matched curves with and without spiral transition curves and found that curves with spiral transitions had generally higher serious injury crash rates than standard non-spiral locations. In view of this results, it has been hypothesized that under certain conditions spiral may lead to an underestimation of the sharpness of a curve. A study by Council (1998), one of the coded studies in this synopsis, has identified some of the key variables – type of terrain, degree of curve, road width - that explain the contrasting findings from Zegeer et al. (1991) and Tom (1995).

In a meta-analysis, Elvik et al. (2009) report a general significant 11% reduction of crashes in curves with transition curve compared to curves without transition curve. However, for curve radius between 165-345 metres and especially for curve radius under 165 metres, transition curves were associated with a crash increase (+4% not significant,+112% significant). Thus, in the research literature both positive and negative safety effects of absence of transition curves have been found.

Even though most design standards recommend the use of spiral curves in the transition design, as earlier indicated at least one study indicated that spiral transition may decrease curve safety, possibly by hindering a realistic curve perception. In view of this, Perko (2006) investigated the role of the length of the spiral transition on driver behaviour along two-lane rural roads. The results showed that the most desirable spiral length, which provides advantages in comparison with a tangent-to-curve transition, is equal to the distance travelled during the steering time. The researcher concluded that long spirals lead to more steering and speed corrections and, consequently, lesser safety, in particular if the curve requires a speed reduction for safe travel. Perko developed a model to estimate the desirable spiral length for transitions of sharp horizontal curves on two-lane rural roads based data collected in three studies.

Effects on driving performance

In a simulator study by Helmers & Törnros (2006) the effect of spiral transitions on the speed and the maximal lateral acceleration within curves was studied. Their simulated road environment included rural two-lane highways, with curves with radii of 100, 200 and 400m and spiral-lengths varying between 0 and 0.6 times the radius of the curve. The results indicated that spiral transitions only affected the maximum lateral acceleration in the curve with the smallest radius (100m). The maximal lateral acceleration was in this curve reduced for spiral length of 0.6 times the radius of the curve. Also, the spiral transitions were found to increase the speed on both the approach tangent and the centre point of curves.

In a naturalistic driving data study, Imberg & Palmberg (2015) investigated the relationships between spiral length and speed and lateral acceleration. Seven curves were selected on rural two-lane roads with a posted speed limit of 70 km/h. Only data collected from passenger cars was used, and the driver factors studied were speed and maximum lateral acceleration. The curve geometry factors studied were radius, presence and lengths of spiral transitions and lengths of approach and exit tangent. Regression analyses were used to analyse how these factors influenced the driver behaviour in terms of speed and maximum lateral acceleration. The speed behaviour was also analysed by studying speed profiles. The regression analysis showed that the speed at the centre point (C) increased with longer spiral transition. However, the speed at the point where the spiral transition transfers into the circular curve was found to be independent on the spiral transition length. This result indicates that drivers keep the same speed at a spiral transition as they would have on a tangent. Longer approach spiral transition resulted in smaller speed differentials when approaching the curve. The maximum lateral acceleration in the curve was unaffected by the length of approach spiral transition (Imberg & Palmberg, 2015). Longer exit spiral transitions resulted in smaller speed differentials when leaving the curve (Imberg & Palmberg, 2015).

Since spiral transition curves were found to elicit higher speed at the same time as the maximum lateral acceleration did not increase, the authors conclude that the spiral transition most probably changed the trajectory (Imberg & Palmberg, 2015).

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 What is the relationship between crashes and absence of transition curve

4 studies were selected for coding on the basis of providing information on safety effects of absence of transition curve; 2 studies used rural 2 lane highway road and crash data in USA, 1 study used 2-lane highway and crash data in Iran, and 1 study used a simulated driving method. The 4 studies used different methods and databases, with different lengths of accident periods, differing road characteristics, and all studies used unique analysis models. Below we describe the results of the 4 coded studies.

Zegeer et al . (1991) developed a data base of 10,900 horizontal curves in Washington State with corresponding crash, geometric, traffic, and roadway data variables. This was the primary data base for analysis containing a computerised data base of horizontal curve records for the State-maintained highway system (about 7,000 mi) (11,270 km) in Washington State. The curve files contained information about degree of curve (i.e., curve radius), length of curve, curve direction, central angle, and presence of spiral transition on each curve. The researchers estimated a linear model for accident rate (per million vehicle miles) using a weighted least squares procedure with the weight function being the product of the length of road and ADT.
Based on the analysis of 10,900 horizontal curves in Washington State, the variables found to have a significant effect on accidents are: traffic volume, degree of curve, length of curve, roadway width, the presence of spiral transitions, and super elevation (Zegeer et al., 1991).

The magnitude of the effect was studied from the above predictive model as well as from other analyses. Depending on the degree of curve and central angle, the effect of having a spiral transition was found to range from about 2 percent to 9 percent based on the predictive model. The influence of central angle and degree of curve was generally a function of the form of the model. An overall reduction of 5 percent was determined to be the most representative effect of adding spiral transitions to a curve (Zegeer et al., 1991, page 139).

Council (1998) investigated the safety effects of transition curves under different horizontal and vertical curvature conditions. Crash and roadway inventory data, covering the period 1982-1986 and containing over 15,000 transition sections (curve ends) in the state of Washington, were used for the analysis. . Council conducted contingency table analyses and linear logistic modelling to explore differences in the probability of one or more crashes on the two types of transitions (spiral vs. non-spiral) within each of three types of terrain—level, rolling, and mountainous. The analysis of the safety effect of spiral transitions in level, rolling and mountainous terrain took into account other confounding variables such as degree of curvature, lane and shoulder width, and roadside. The analysis showed both safety benefits and dis-benefits of spiral transitions, depending on other features. It was shown that on level terrain (which might be assumed to have significant preview distance), spirals can increase road safety on sharper curves (those > 3°). In rolling terrain, spirals appeared to improve safety at flatter curves (those ≤ 8°) on minor roads and on principal arterials designed for higher average daily travel (i.e., greater than approximately 4000 ADT). In mountainous areas spirals were found to lead to increases in crashes and therefore their use should be restricted to roads with wider lanes and shoulders.

The explanation for the more restricted safety effects on rolling terrain maybe that drivers underestimate the sharpness of curves due to shorter sight distances. When the curve is constructed with a transition curve the beginning of the curve is less sharp and only this beginning is observed. In flat terrain with longer sight distances sharp curves are likely less unexpected. Another explanation of the more favourable effects of transition curves in flat terrain is that the transition curve produces smoother steering wheel movements (and more gradual changes in super-elevation and improved side friction). It may be assumed that the central mechanism is sight distance which determines whether transition curves favourably affect steering wheel movements. Side friction and view through the curve may unfavourably influence curve predictability and speed.

Zakowska (2009) studied effects of driving through rural roads with different geometric parameters in a simulator environment on driving behaviour. In each driving scenario participants had to negotiate 20 horizontal curves: 12 without clothoids and 8 with clothoids. Three outcome measures were calculated:
- Speed: average speed on curve, approaching speed at the section where curve with constant curvature begins, and speed in the middle of curve.
- Dispersion of Trajectory (DT): This indicator quantifies the dispersion of driver's trajectory on curve (*tv*) with respect to his average trajectory (*ta*).
- Pathologic Discomfort. The PD is a surrogate measure of safety that has a proven correlation with accident rate. PD corresponds to the area between the curve of the driver's lateral acceleration and the curve of the theoretical lateral acceleration, based on the average speed and the real curvature of the road. The PD measures takes into account the local variability of lateral acceleration, consequence of the driver's need for correcting his trajectory to follow the geometry of the road axis. Repeated local oscillations of lateral acceleration represent a violation of driver expectancy. (Zakowka, 2009; Calvi, 2015). To allow for comparison between curves, DT and PD values were divided by length of curve.

Table 2 shows the effects of the absence of clothoids on driving performance in curves with 300 and 500m curve radii on 100 km/hr roads.

Table 2 Effects of absence of clothoids on driving performance in curves on 100 km/hr. roads in a simulated environment (Zakowska, 2009).

Curve radius	Speed	DT	PD
300 metres radius	-3,5% (ns)	+16,5% (sign.)	+67,2% (sign.)
500 metres radius	-4,0% (ns)	+86,3% (sign.)	+82,3% (sign.)

Zakowska found that curves without clothoids were driven at a somewhat lower speed than the same geometry curves with clothoids. This effect is likely caused by a better interpretation of road geometry by the driver. In other words, drivers perceive the curve better when it is preceded by a clothoid and consequently adopt a higher speed (on average, 3% higher speed) without significant deceleration before the curve. The absence of clothoids led to larger dispersion of trajectory, especially in curves with larger radius, and larger pathological discomfort, i.e. worse performance on two driving indicators linked to driver expectation and safety.

In a study in Iran, Aram (2010) investigated the relationship between geometric factors related to horizontal curves and crashes on 2-lane highways. He took into account traffic volumes and various longitudinal and horizontal design elements such as degree of curve, curve length, super elevation, presence of transition curves, lane width, shoulder type and width, clear slope, type of obstacles, Stopping Sight Distance, vertical alignment, distance to adjacent curves etc. Based on Poisson based regression the study established that traffic performance (million veh-km travel), degree of curvature, length of curvature, length of spiral curve; super-elevation and shoulder width were significant predictors of crashes. However, model statistics show that the model suffers from overdispersion, which results in an underestimation of the standard error of the parameter-estimates. Therefor the significance test is not reliable.
The model revealed that an increase in the *length of spiral curves* and shoulder width led to reductions in crashes, however not correctly tested for statistical significance.

2.3 ANALYSIS METHODS AND RESULTS

2.3.1 Introduction

The estimates in the 4 coded studies were subject to different statistical models, using different sets of dependent and independent variables. Therefore the estimates are not directly comparable and the results do not lend themselves to meta-analysis.

The effects of absence of transition curve can be summarized as follows:

- 1 USA study showing that spiral transition reduced curve crashes by 5%, with no evidence for a differential effect depending upon sharpness of the curve (Zegeer et al., 1991)
- 1 USA study showing that transition curves have the most safety effect preceding sharp curves at flat terrain and have less or negative safety effect on curves in rolling or mountainous areas (Council,1998)
- 1 USA simulator study showing that absence of transition curves leads to worse driving performance in curves as measured by indicators concerning the dispersion of driver's trajectory on curve (tv) with respect to his average trajectory (ta) and indicators comparing the curve of driver's lateral acceleration and the curve of the (optimum) theoretical lateral acceleration (Zakowska, 2009).
- 1 Iranian study showing that an increase in the length of a spiral curve was associated with reduced crash rate, however not significantly tested as the model suffered from overdispersion (Aram, 2010)

Table 1 presents an overview of the main features of coded studies (sample, method, outcome indicator and results).

Table 1. *Description of coded studies*

Author, Year	Sample and study design	Method of analysis	Outcome indicator	Main result
Aram, 2010	2007 crash data of 502 horizontal curves on two-lane highways in Iran.	Poisson regression model. Based on Poisson based regression(it is not clear if NB regression was used) the study establishes that traffic performance (million veh-km travel); degree of curvature, length of curvature, length of spiral curve; super-elevation and shoulder width are significant predictors of curve-related crashes.	Number of horizontal curve-related crashes	According to the author the model shows that an increase of the spiral curve length relates to a decrease in crashes. However, the results are not correctly tested for significance as the model suffers from overdispersion.
Council, 1998	The article presents a US study to the evaluation of the use of spiral curves. The presence and absence of a spiral curve is evaluated. The used database was the Washington State files for the years 1986 and earlier. The system contains crash information on approximately 34,000 crashes per year, roadway inventory and traffic information on 11 200 km (7,000 mi) of roadway, and a separate file of 10,900 horizontal and vertical curves, which includes information on spiral transitions. These crash, roadway, traffic, and curve files were linked for analysis, and have been cleaned. Crash and inventory data from the years 1982 to 1986 were included, and supplemental data on the nature of the roadside on 1,000 of these curves was extracted from a separate file developed earlier for FHWA. The final file on spirals contained 2,108 spiral and 6,163 non-spiral records (8,271 analysis records).	Linear logistic regression models were developed in three terrain categories (level, rolling, moun-tainous). Models using the pure spiral data were developed first, and verification models from the "spiral plus" file were then developed. In each case, alternative models were deve-loped until all quadratic and interaction terms retained were significant. To ensure that the spiral coefficient captured only the effect of the spiral, all confounders identified in the contingency table analyses were retained in the model regardless of significance level. Included confounding variables were: ADT, degree of curve, shoulder width, surface width, recovery area distance, road side skating. Using the linear logistic regression procedure, the researchers modelled the log of the ratio of the probability of one or more crashes to the pro-bability of no crashes as a function of the predictor variables.	The probability that a given location will have one or more crashes in a 5-year period. This probability can be denoted as p = Pr(Y = 1|x), if x is the vector of explanatory variables.	The level terrain model suggests that with curves with a degree of curve higher than 3 (thus sharper), a spiral is beneficial for road safety. The rolling terrain model for minor roads suggest that spirals are beneficial. The rolling terrain model for arterial roads suggests that spirals are beneficial for busier roads. The rolling terrain models contradict each other. The mountainous terrain model suggests spirals are beneficial for wider roads (wider than 7 m) but add very high risks to smaller roads. The odds ratios which can be estimated from the model and tells you the risk of the presence/ absence of the spirals are very sensitive for any changes in any of the values of the variables. CMFs are estimated for average values but will change for different values of the model variables. The results tentatively indicated that in level terrain (which might be assumed to have significant preview distance), spirals can be beneficial on sharper curves (those > 3 degrees). In rolling terrain, they appeared beneficial at flatter curves (those ≤ 8 degrees) on minor roads; and on principal arterials designed for higher ADTs (i.e., greater than approximately 4,000 ADT). In mountainous areas, the results indicate that spirals should be used very seldom, and only on roads with wider lanes and shoulders.
Zakowska, 2009	The study investigates the relationship between clothoids as transition curves and driver behaviour in a simulator environment. The study comprises a simulator and questionnaire study among 31 young (relatively inexperienced) Italian drivers. Only the simulator study results are of immediate interest	The simulator study investigates 3 rural road types (50; 70 and 100km/h) with varying combina-tions of tangent and curve lengths, curve radii, visibility through the curve and the transition curves. 31 drivers were tested in laboratory conditions of the CRISS driving simulator. Each subject was driving three sections of virtual roads repre-senting three roads categories. All driving scenarios were composed of twenty horizontal curves divided by straight	The outcome indicators were: - Average speed in curve (km/h) - Average transverse acceleration (m/s2) - Average lateral displacement in lane (m)	Speeds on sections with transition curves were significantly higher with no sudden decelerations approaching the curves whereas pathologic discomfort (a function of transverse accelerations resulting from steering corrections) and lateral displacement in the lane was much higher on sections without transition curves (in the form of a clothoid in this case). Curves without clothoids were driven at lower speed, than the same geometry curves with clothoids (not significant). This effect is stronger at curves with larger radii, and it increases with the raising road category. It should be caused by a better interpretation of

Author, Year	Sample and study design	Method of analysis	Outcome indicator	Main result
		sections, organized in random sequence. Only the results for the 100km/h (*Scenario C*) roads were coded although the results consistently show (across all road types) that the application of transition curves between tangents and horizontal curves improves driver behaviour. The analysis of clothoid effects have been developed only for curves of radius R = 300 m and R=500 m.		geometries by driver that perceives better the curve when it is preceded by a clothoid and consequently he adopts a higher speed (in average, +3%) without significant deceleration before the curve. Conclusion: The lack of transition curves result in lower speeds through the curve, lead to a higher degree of discomfort and result in drivers making more steering corrections in the curve (more lateral displacement)
Zegeer 1991	Washington State curves were selected as the primary data base for analysis because there was an computerized data base of horizontal curve records for the State-maintained highway system (about 7,000 mi) (11,270 km) in Washington State. The curve files contained such infor-mation as degree of curve (i.e., curve radius), length of curve, curve direction, central angle, and presence of spiral transition on each curve.	Based on the analysis of 10,900 horizontal curves in Washington State, the variables found to have a significant effect on accidents were traffic volume, degree of curve, length of curve, roadway width, the presence of spiral transitions, and super elevation.	Number of total accidents on the curve in a 5-year period	The model that was used in the development of accident reduction factors for roadway widening, curve flattening (non-isolated curves), and the addition of a spiral transition was as follows: $A = [\,(1.55)\,(L)(V) + .014\,(D)(V) - (.012)\,(S)(V)\,]\,(.978)^{W-30}$ where, . A = Number of total accidents on the curve in a 5-year period; L = Length of the curve in mi (1.6 km); v =Volume of vehicles in million vehicles in a 5-year period passing through the curve (both directions); D =Degree of curve; S = Presence of spiral transitions on both ends of the curve, where S = 0 if no spiral exists, and S = 1 if spirals do exist; W=Width of the roadway on the curve in ft (.3048 m) An overall reduction of 5 percent was determined to be the most representative effect of adding spiral transitions to a curve in view of the predictive model and other related analyses. While one may expect that spiral transitions are more beneficial on sharp curves than mild curves, such a differential effect was not adequately supported from the analysis.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature search aimed at identifying the highest quality and most recent studies for quantifying the relationship between absence of transition curves and crash occurrence (number of crashes) and crash severity. Therefore the document search strategy was primarily aimed at studies undertaken in Europe and published in recognized scientific journals and publications. Failing that, the search fell back on older studies and/or studies from other parts of the world but with the provison that these were published in recognized scientific publications. The Scopus and TRID databases were searched in the formal literature search. The literature search was done in 2016. All searches were filtered on English results only.

To select papers relating to road safety in Scopus, the following query was used: ((road and casualt*) or (road and injur*) or (road and accident*) or (road and crash*) or (traffic and injur*) or (traffic and casualt*) or (traffic and accident*) or (traffic and crash*)).

To select papers relating to road safety in TRID, the following query is used: (collision* or crash* or accident* or injur* or casualt*) AND (traffic or road).[1]

The aforementioned queries were combined with a query to select papers relating to the risk factor absence of transition curves: ("compound curves" or "compound curve" or (curve* and spiral*) or "transition curves" or "transition curve")

These queries were combined in Scopus and TRID to search for literature about the risk factor frequent curves. To distinguish literature from Europe and Worldwide, the results were loaded into Mendeley, where the following query was used to identify literature from Europe: (Italy or Ireland or Hungary or Greece or Germany or France or Finland or Estonia or Denmark or Czech or Cyprus or Croatia or Bulgaria or Belgium or Austria or Scotland or England or Britain or United Kingdom or Sweden or Spain or Slovenia or Slovakia or Romania or Portugal or Poland or Netherlands or Malta or Luxembourg or Lithuania or Latvia).

The result of this search is reflected in table 2.

Table 2 Literature search strategy

search no.	Region	Database	Hits
#1	Europe	Scopus	4
#2	Europe	TRID	11
#3	Worldwide	Scopus	25
#4	Worldwide	TRID	52

[1] The difference in the queries is due to differences in restrictions to the query length between the two sources.

From these reverences all abstracts were reviewed, resulting in an initial selection of only 6 relevant studies. Two more references were added that did not come up in the search for transition curves but for other risk factors.

The search results suggest that this topic has not been extensively studied related to crash risk, or that relevant studies have not been published in English.

Additional references were searched on Google for the literature review on transition curves, as part of this synopsis.

3.2 LIST OF STUDIES

A list of studies considered (and of which the first 4 were selected for coding) are listed below:

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Helmers, G. & Törnros, J., (2006). *Effekt av övergångskurvor på förares säkerhetsmarginal samt inverkan av träning - ettförsök i körsimulator (Effect of transition curves on drivers' safety margin and the impact of training – an attempt in the driving simulator*). VTI, Sweden.

Imberg, J. & Palmberg, A. (2015). *How curve geometry influences driver behavior in horizontal curves. A study of naturalistic driving data*. Master's thesis Chalmers University of Technology, Gothenburg, Sweden.

Mannering,F.L, Washburn, S.S., & Kilareski, W.P. (2011). *Principles of highway engineering and traffic analysis*, 4th edition. Wiley, Hoboken, New Jersey.

PIARC (2004). *Road safety manual : Printed version and CD-ROM* (2004).

Perco, P. (2006). Desirable Length of Spiral Curves for Two-Lane Rural Roads. *Transportation Research Record, 1961*, 1–8.

Tom, G. (1995). Accidents on Spiral Transition Curves. *ITE Journal*, *65*, 49–53.

Synopsis 15: Alignment deficiencies - Frequent curves

1 Summary

J.W.H. van Petegem, G. Schermers. (SWOV, Sept. 2016)

1.1 COLOUR CODE: GREY

Only three relevant papers were found suitable for coding. All three studies indicate that an increased risk is found for a higher degree of bendiness . However, two of the papers are by the same author. and research group. The number of coded papers is insufficient to allow for a meta-analysis and an overall effect is difficult to isolate since the number of papers is too small and the indicator itself does not appear to have a clear causal relation with crashes. Also, the coded studies refer to other studies where no relation or the opposite effect was found.

1.2 KEYWORDS

Curve density, curve frequency, curvature change rate, bendiness, frequent curves, crashes, crash rate, cumulative angle, road safety

1.3 ABSTRACT

Curves are considered to be a risk factor in the design of roads. Most research on the risk of curves focuses on individual curves, only a few studies focus on the frequency of curves. Findings from those studies are inconsistent. Five studies report a higher risk of crashes on roads with a higher frequency of curves or found no relation, while three more recent studies report a lower risk on crashes with a higher frequency of curves. Studies reporting lower crash numbers on roads with more curves hypothesise that this might be due to a better anticipation of drivers on curves. Checks are missing however if the number of curves is related to the amount of traffic or to safety measures on more dangerous curves. The findings on frequent curves are therefore inconclusive.

1.4 BACKGROUND

1.4.1 Definitions of frequent curves

There are different ways in which Frequent curves can be measured:

- Absolute number of curves
- Number of curves per kilometre
- Sum of all deflection angles divided by the road length
- Length of curves as a percentage of the road length

There are also different terms in use, like the curvature change rate, bendiness, curve frequency, curve density or bend density.

1.4.2 How does the frequency of curves affect road safety?

Tight curves are considered a risk factor in the design of roads. Most research on the risk of curves focuses on individual curves, only a few studies focus on the frequency of curves. Findings from those studies are inconsistent. Some studies report a higher risk of crashes on roads with a higher frequency of curves, while a few other recent studies report a lower risk on crashes with a higher frequency of curves. Therefore, no general rule can be applied as to the question if a higher frequency of curves is related to a higher number of crashes.

1.4.3 Which safety outcomes are affected by frequent curves?

The outcomes variables are different in different studies of the relationship between frequent curves and crashes. Outcomes are measured as the number of crashes, the severity outcome of crashes and crash occurrence (zero or one or more) on a road.

1.4.4 How is the effect of frequent curves on crashes studied?

The coded studies on frequent curves has a cross sectional study design. Logit or log linear models are developed to study the relationship between crash numbers, or occurrence or crash severity outcome and road design and exposure variables. The study design helps to find evidence for an empirical relationship between crashes and frequent curves, but does not identify a causal relationship.

1.5 OVERVIEW RESULTS

A total of 10 studies were initially selected as candidate studies for coding. None of these studies were found to be suitable, as they did not relate to frequent curves but to single curves, or did not report findings on frequent curves. An additional search of Google with the term bendiness resulted in four additional studies, of which three were found to be suitable for this project to be coding in SafetyCube. In an attempt to find additional studies, some of the references in these studies were consulted but not found suitable for coding have been looked up, but have not been coded.

The final selected studies found an empirical relationship between an increase in frequent curves and a decrease in crashes.

Despite these common findings, other studies as referred to by the included studies found an increase in crashes at roads with a higher degree of bendiness or no relation between bendiness and crashes. A constraint of the above findings is that two of the studies are by the same author and in the same region, although at a different network level. An overall conclusion regarding the effect of frequent curves on crashes cannot be drawn on the basis of these results. Therefore there are not enough study results to draw conclusions.

It is important to keep in mind that the results from the coded studies on the risk factor frequent curve does not represent a causal relationship with crashes, but merely that there is a relationship given the conditions that were taken into consideration. Other (confounding) factors might be causing the decrease in crashes at a network or route level, where an increase in bendiness is measured. The authors of the coded studies hypothesise that higher attention levels and lower speeds might be the reason for lower crash numbers on networks or roads with higher bendiness levels.

An important limitation of the coded studies is that tests for co-linearity are missing.

More research is needed to identify in which situations the risk factor frequent curves might be used for the purpose of network screening or prioritisation of measures.

1.6 NOTES ON ANALYSIS METHODS

The amount of studies on frequent curves is very limited. There is a large body of research focused on single curves or on subsequent curves. However, the number of studies relating curve frequency to crashes is very limited. Three studies were found, showing similar results and indicating that a higher degree of bendiness relates to a lower number amount of crashes. Although the coded studies point in the same direction, references from the coded studies had contradictory or no significant findings. Furthermore, there doesn't seem to be a causal relation between the number of curves on a road, and the number of crashes. A lower speed and higher awareness is hypothesized as a possible explanation for these findings. There could however also be a relationship between exposure and bendiness, and safety measures and bendiness which could explain why road (networks) with a higher degree of bendiness are related to less crashes. Although the coded papers showed interesting methodologies, the methodologies do not seem to provide enough evidence to suggest causality between the number of curves and a decrease in crashes.

2 Scientific overview

2.1 LITERATURE REVIEW

The amount of studies related to frequent curves is limited. No relevant studies were found in Scopus or TRID using the following query ("curve frequency" or "number of curves" or "curve density" or "curve frequencies" or "curve densities" or "curvature change rate" or "subsequent curves"). An additional search with Google using the keyword bendiness resulted in the selection of three relevant studies for coding (Dantas, Fowler, and Koorey 2007; Haynes et al. 2008; Jones P et al. 2012).

Bendiness can be measured in several ways:

- Absolute number of curves
- Number of curves per kilometre
- Sum of all deflection angles divided by the road length (similar to the curvature change rate)
- Length of curves as a percentage of the road length

All three studies found an empirical relationship between frequent curves and crashes that indicated that a decrease in crashes was found when bendiness increased.

The relationship is however not causal. The authors of the three studies hypothesise that their findings might be due to a higher driver attention level on roads (or road networks) where there is a higher degree of bendiness, which also might cause drivers to drive slower. The coded studies do not explore the possible relationships between bendiness and exposure or safety measures and bendiness.

Furthermore, two studies (Shankar, Mannering, and Barfield 1995, 1996) – as referred to in the coded studies – found an increase in crashes at roads where the degree of bendiness was higher. Whereas two other studies (Noland and Oh 2004; Walmsley, Summersgill, and Binch 1998) did not find an empirical relations between bendiness and crashes.

This leads to the conclusion that a general relationship between bendiness and crashes cannot be isolated at this point. Since the coded studies do not provide details of the exact conditions under which the effects were established, a generalised conclusion, other than increased bendiness appears to lead to more crashes, is not possible. More research is needed to identify in which situations the risk factor frequent curves might be used for the purpose of network screening or prioritisation of measures.

2.2 DESCRIPTION OF STUDIES

The three coded studies analysed the relationship between frequent curves and crashes on different spatial levels. Two studies analysed the risk factor on a network level (Haynes et al. 2007; Jones P et al. 2012) with both studies using data from the same region, although with different network area sizes. The network area sizes were defined by administrative borders. Network area sizes in Haynes et al were defined by districts with a typical area size of 40 km diameter whereas the network area size in Jones et al. was defined by wards, with a typical area size of 5 km diameter. Both studies analysed the relationship between the number of crashes in the area with some bendiness variable for the whole network.

Dantas et al. followed a different approach and studied the relationship between crashes and frequent curves on a route level. Routes were defined as all possible road sections one kilometre upstream and downstream of a crash site or randomly selected location. For each location the bendiness was measured based on all possible combinations of road sections linked to the location.

All three studies used different regression analysis techniques. Haynes et al. studied the risk factor with a standard log linear regression analysis using a negative binomial probability distribution. Jones et al. used a random intercept multilevel negative binomial model structure to correct for spatial dependencies between Wards, falling in the same regional district. Both of these studies had crash counts on the network as the outcome variable. Dantas et al. did a binary logistic regression analysis, with the outcome variable defined as the probability of a crash (one or more) occurring at a location.

While all three studies included several different bendiness variables, all three studies included the cumulative deflection angle divided by the road length.

Despite the differences between the three studies, they came to the same conclusion. Table 2 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 2 Description of coded studies

Author, year	**Risk factor**	**Study type**	**Outcome variable**	**Main outcome - description**
Robin Haynes, Andrew Jones, Victoria Kennedy, Ian Harvey, and Tony Jewell. 2007	Bendiness: Cumulative deflection angle / road length	Cross sectional – Negative Binomial regression analysis	Number of accidents per region (district level UK)	An empirical relation is found for a higher amount of crashes for districts with a higher degree of bendiness
Dantas, A., M. Fowler, and G. Koorey. 2007	Bendiness: Cumulative deflection angle / road length	Cross sectional – binary logistic regression analysis	The probability of one or more crashes on a route	An empirical relation is found for a higher chance on a crash occurrence for routes with a higher degree of bendiness
Jones, Andrew P., Robin Haynes, Ian M. Harvey, and Tony Jewell. 2011	Bendiness: Cumulative deflection angle / road length	Cross sectional –Random intercept multilevel negative binomial regression analysis	Number of accidents per region (ward level UK)	An empirical relation is found for a higher amount of crashes for districts with a higher degree of bendiness

There were some limitations to the coded studies. None of the studies reported on checking for co-linearity between the predictors. This is an important limitation, as it is not unlikely that there is relation between bendiness and exposure. The study of Haynes et all. (2007) showed that when bendiness was included in the model, the parameter estimate of the exposure variable changed. This seems to suggest that co-linearity is present between the predictors. Another limitation is that the problem of possible confounding factors, like a possible relations between bendiness and exposure or safety measures and bendiness, are not discussed in the studies.

Based on the number of studies and the differences between the studies, a meta-analysis or a vote count was not possible.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature search aimed at identifying the highest quality and most recent studies for quantifying the relationship between frequent curves and crash occurrence (number of crashes) and crash severity. Therefore the document search strategy was primarily aimed at studies undertaken in Europe and published in recognized scientific journals and publications. Failing that, the search fell back on older studies and/or studies from other parts of the world but with the provision that these were published in recognized scientific publications. The Scopus and TRID databases were searched in the formal literature search. All searches were filtered on English results only. The literature search was done in 2016.

To select papers relating to road safety in Scopus, the following query was used: ((road and casualt*) or (road and injur*) or (road and accident*) or (road and crash*) or (traffic and injur*) or (traffic and casualt*) or (traffic and accident*) or (traffic and crash*)).

To select papers relating to road safety in TRID, the following query is used: (collision* or crash* or accident* or injur* or casualt*) AND (traffic or road).[1]

The aforementioned queries were combined with a query to select papers relating to the risk factor frequent curves: ("curve frequency" or "number of curves" or "curve density" or "curve frequencies" or "curve densities" or "curvature change rate" or "subsequent curves")

These queries were combined in Scopus and TRID to search for literature about the risk factor frequent curves. To distinguish literature from Europe and Worldwide, the results were loaded into Mendeley, where the following query was used to identify literature from Europe: (Italy or Ireland or Hungary or Greece or Germany or France or Finland or Estonia or Denmark or Czech or Cyprus or Croatia or Bulgaria or Belgium or Austria or Scotland or England or Britain or United Kingdom or Sweden or Spain or Slovenia or Slovakia or Romania or Portugal or Poland or Netherlands or Malta or Luxembourg or Lithuania or Latvia).

The search results based on the described search strategy is presented in table3.

Table 3 Literature search results

search no.	Region	Database	hits
#1	Europe	Scopus	2
#2	Europe	TRID	5
#3	Worldwide	Scopus	11
#4	Worldwide	TRID	15

[1] The difference in the queries is due to differences in restrictions to the query length between the two sources.

From these reverences all abstracts were reviewed, resulting in an initial selection of 10 studies. None of these ten studies appeared to be relevant for the risk factor frequent curves.

Since the search strategy resulted in the selection of zero relevant studies, an additional search was done with Google, using the keyword bendiness. This resulted in the selection of 4 additional relevant studies, of which three selected for coding.

The search results suggest that this topic has not been extensively studied.

3.2 LIST OF STUDIES

A detailed list of studies considered is listed in the following paragraphs:

3.2.1 Coded studies

Dantas, A., M. Fowler, and G. Koorey. 2007. "Effect of Road Network Bendiness on Traffic Crash Occurrence." Retrieved July 21, 2016 (http://ir.canterbury.ac.nz/handle/10092/689).

Haynes, Robin, Andrew Jones, Victoria Kennedy, Ian Harvey, and Tony Jewell. 2007. "District Variations in Road Curvature in England and Wales and Their Association with Road-Traffic Crashes." *Environment and Planning A* 39(5):1222–37. Retrieved March 29, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-34249782299&partnerID=tZOtx3y1).

Jones, Andrew P., Robin Haynes, Ian M. Harvey, and Tony Jewell. 2012. "Road Traffic Crashes and the Protective Effect of Road Curvature over Small Areas." *Health & Place* 18(2):315–20. Retrieved March 29, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84856578690&partnerID=tZOtx3y1).

3.2.2 Studies considered for coding but not coded

Ambros, Jirí, Veronika Valentová, and Jirí Sedoník. 2016. "Developing Updatable Crash Prediction Model for Network Screening: Case Study of Czech Two-Lane Rural Road Segments." *Transportation Research Record: Journal of the Transportation Research Board* (2583):pp 1–7. Retrieved (http://docs.trb.org/prp/16-1817.pdf).

Chen, Tao, Lang Wei, and Wei-xin Zhou. 2011. "Study on the Relationship between the Horizontal Alignment Indices and Traffic Safety in Mountainous Freeway." Pp. 2319–25 in *ICCTP 2011*. Reston, VA: American Society of Civil Engineers. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-80053301445&partnerID=tZOtx3y1).

Choueiri, Elias M., Ruediger Lamm, Juergen H. Kloeckner, and Theodor Mailaender. 1994. "SAFETY ASPECTS OF INDIVIDUAL DESIGN ELEMENTS AND THEIR INTERACTIONS ON TWO-LANE HIGHWAYS: INTERNATIONAL PERSPECTIVE." *Transportation Research Record* (1445):p. 34–46. Retrieved (http://onlinepubs.trb.org/Onlinepubs/trr/1994/1445/1445-004.pdf).

Dell'Acqua, Gianluca, Francesca Russo, and Salvatore Antonio Biancardo. 2013. "Risk-Type Density Diagrams by Crash Type on Two-Lane Rural Roads." *Journal of Risk Research* 16(10):1297–1314. Retrieved March 29, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84887014872&partnerID=tZOtx3y1).

Dell'Acqua, Gianluca and Francesca Russo. 2010. "Accident Prediction Models for Road Networks." P. 11p in. Retrieved (https://trid.trb.org/view/1100358).

Haynes, Robin et al. 2008. “The Influence of Road Curvature on Fatal Crashes in New Zealand.” *Accident; analysis and prevention* 40(3):843–50. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-42949145054&partnerID=tZOtx3y1).

Hosseinpour, Mehdi, Ahmad Shukri Yahaya, Seyed Mohammadreza Ghadiri, and Joewono Prasetijo. 2013. “Application of Adaptive Neuro-Fuzzy Inference System for Road Accident Prediction.” *KSCE Journal of Civil Engineering* 17(7):1761–72. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84886299253&partnerID=tZOtx3y1).

Lamm, R., A. Beck, and K. Zumkeller. 2000. “ANALYSIS AND EVALUATION OF INTERRELATIONSHIPS BETWEEN TRAFFIC SAFETY AND HIGHWAY GEOMETRIC DESIGN ON TWO-LANE RURAL ROADS.” Pp. p. 557–70 in. Retrieved (https://trid.trb.org/view/656926).

Parida, M., S. Jain S, and Vishrut Landge Suresh. 2006. “Stochastic Modeling for Traffic Crashes on Non Urban Highways in India.” P. 13p in. Retrieved (http://arrbknowledge.com).

Pour Hossein, Mehdi, Joewono Prasetijo, and Seyed Ghadiri Mohammad Reza. 2011. “Quantifying the Safety Performance of Rural Roadways Using Two Models.” P. 16p in. Retrieved (http://onlinepubs.trb.org/onlinepubs/conferences/2011/RSS/2/Pour,M.pdf).

Wu, Lingtao, Dominique Lord, and Yajie Zou. 2015. “Validation of Crash Modification Factors Derived from Cross-Sectional Studies with Regression Models.” *Transportation Research Record: Journal of the Transportation Research Board* (2514):pp 88–96. Retrieved (http://dx.doi.org/10.3141/2514-10).

3.2.3 Additional relevant references from selected studies

From the selected studies, a few additional relevant studies to the riskfactor emerged, which are listed below.

Barker, J., S. Farmer, and M. Taylor. 1999. The Development of Accident-Remedial Intervention Levels for Rural Roads. Prepared for the Department of the Environment, Transport and the Regions DETR, Road Safety Division. Retrieved (http://swov.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwbV1LS8QwEA6iF9GDi4rrA-YHbF_bR9qr2y7iSW0RPC0xD1hYWmir4p_a3-hM6lpRj3kNJCEzycz3TRgL567v_NIJJjRCKInmNE0MRzOYJfE8imWg04ALQQHe4ja5f46eSl6NHLGd4617b97ceuMNWH_PELffk7iEqGookprRXyu0h9OY2weYvyBgFg46GlXf80QdaCIQTNierk_ZFvcB1IjMgcaAkJK-8uwd8s0RcQPWP5CHsKHeHeBtElpKigFtI1TnwkOrLVzctuC9DXIq9zupVFOMtLUZfOctB1Er21xqQh93kBdVOYMSxcKjMLr_gHw9kMzP2HRZVIs7h6a1-vLtrOzEw3N2LAgPX_eWN6cuGGRccYMHTHC00TrIUpO9RKH2ZZxmCs_tlE3-Crr8r_KKHQ6pCsjtcM32-_ZV3wyr-wlhFpTb).

Noland, Robert B. and Lyoong Oh. 2004. “THE EFFECT OF INFRASTRUCTURE AND DEMOGRAPHIC CHANGE ON TRAFFIC-RELATED FATALITIES AND CRASHES: A CASE STUDY OF ILLINOIS COUNTY-LEVEL DATA.” Accident Analysis & Prevention 36(4):p. 525–32. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-1942537196&partnerID=tZOtx3y1).

Shankar, Venkataraman, Fred Mannering, and Woodrow Barfield. 1996. “Statistical Analysis of Accident Severity on Rural Freeways.” Accident Analysis & Prevention 28(3):391–401.

Shankar, Venkataraman, Fred Mannering, and Woodrow Barfield. 1995. “Effect of Roadway Geometrics and Environmental Factors on Rural Freeway Accident Frequencies.” Accident Analysis & Prevention 27(3):371–89.

Walmsley, D. A., I. Summersgill, and C. Binch. 1998. Accidents on Modern Rural Single-Carriageway Trunk Roads. Prepared for the Highways Agency, Traffic, Safety and Environment Division. Retrieved (http://swov.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMwbZ3LSsQwFIaD6EZ04aDieIHzANPb9JJmOY4dxJXoILgaYi4ijimoVXHvg3tOqhTUbektITl_cvJ_CWPpNIyDXzHBplZKrVBOs8JylEFR5NMsV4nJEi4lLfBW58XVfXZ3w5cDI_aTeGvf67fQraPe6x9ZYvsjhVWIoYZWUgWqHkF8Zc79BCyekzELH90ZQuBij20ZAghGbMO4ffY5U4rO7exaqB28-JPHoKG9LoBm6WsT4AewETxSDgu65tU9Q1NL3YZw3RhvDwccVwKO04A8GXhXCzMPTE4AhYZ2gJjArbSm-wDpNFQDuQYXTz06fsDGi205vwz0Z1ffGZuVL056yHYludxd52k4fcRAcMotdhvJUXlNIkorHrLUxCovhcbeOGajvy86_u_iCdvu6TpKJpyyTSyfOevr7AvqY4Wq).

Synopsis 16: Alignment deficiencies - Densely spaced junctions

1 Summary

G. Schermers and J.W.H. van Petegem (SWOV, Sept. 2016)

1.1 COLOUR CODE: GREY

Increased junction density can contribute to an increase in crashes, as a result of an increase in the conflict potential. However, research into the effect is inconclusive. The fact that increased junction density increases total crashes but seems to reduce crashes among pedestrians suggests that increased junction density should only be advocated in urban areas where pedestrians are the predominant mode and where motorised traffic is low.

1.2 KEYWORDS

Crashes, injuries; intersection/junction density; intersection/junction spacing

1.3 ABSTRACT

Junction density has been identified as a risk factor although the results of research into the effect of junction density on crash frequency and/or crash severity (number and extent of injuries) is inconclusive. Some studies indicate that denser street networks with higher densities of junctions lead to fewer crashes across all severity levels. Other studies reveal the opposite with increases in the density of certain junction types leading to significantly more crashes of a certain type or of all crashes.

1.4 BACKGROUND

1.4.1 Definitions of intersection density

For the purposes of it being a risk factor intersection density is defined as the total number of intersections per unit area or unit length and is usually expressed as a number per square kilometre or number per kilometre.

1.4.2 How does intersection density affect road safety?

Intersection density is a measure of road network density and the higher the value the more complex the network. For certain road user groups a dense road network with many intersections has advantages whereas for other this becomes a distinct disadvantage. For pedestrians and cyclists, dense road networks are preferable since they drastically improve accessibility. Intersection density has been found to have the largest effect on walking (Ewing and Cervero, 2010[1]) with increasing density leading to significantly more walking. One of the most important factors for increasing transit use and reducing miles driven. For motorised traffic dense road networks with many intersections mean more conflicts with crossing and turning traffic, resulting in more stops with higher delays. However, fewer intersections (therefore lower density) implies higher demand on these intersections (traffic is more concentrated because of the fewer intersections) with the potential risk of higher speeds due to the higher length of road links between junctions. The increased interaction (resulting from increased intersection and roadway density) between

[1] Ewing, R and Cervero, R (2010). Travel and the Built Environment – Meta analysis. Journal of the American Planning Association Volume 76, Issue 3. Chicago, Illinois, USA

vulnerable road users (pedestrians, cyclists etc) and faster and heavier motorised traffic may increase the risk for crashes and serious injuries.

1.4.3 Which safety outcomes are affected by intersection density?

The effects of intersection density on road safety have been studied in terms of a number of safety outcomes but predominantly in terms of crash frequency (number of crashes) and crash severity (number of injured persons). More often than not studies disaggregate the crash outcomes by level (Killed, seriously injured etc.) and/or by type of road user group affected (motorists, cyclists, pedestrians etc.). Studies have also been carried out where other related safety outcomes such as speed, vehicle-kilometres travelled, traffic volumes and other surrogates have been measured. For the intents of this synopsis the focus is on the primary safety outcome, namely the effect of intersection density on traffic crashes and/or injuries.

1.4.4 How is the effect of intersection density on crashes studied?

The majority of international literature researches the effect of intersection density by developing Accident Prediction Models (APMs) through the application of Generalised Linear modelling (GLM) statistical techniques. The majority of studies investigate the relationship between the number of crashes (dependant variable) and any number of road design and other features (the independent or predictor variables) and take the form of Poisson or Negative binomial (NB) models.

The synopsis focusses on studies conducted between 2011 and 2016. Due to a lack of suitable and recent European studies, these include studies from primarily the USA.

1.5 OVERVIEW RESULTS

A total of 14 studies were selected as candidate studies for coding. Of these only 5 were found to be suitable and provided sufficient methodological detail allowing the effects to be coded. The results of the selected studies are mixed and do not all point in the same direction. The reason for this lies in the differences in the methodological approaches followed and the fact that the multiple regression models comprising different sets of dependant and independent variables were used. Furthermore, the effects are calculated for different (Sub)sets of crash data with two studies establishing effects between junction density and all crashes and three reporting the effects on bicycle crashes, child pedestrian crashes and pedestrian crashes. Meta-analysis of these results was therefore not sensible nor advised (Elvik et al, 2009[2]).

Of the two studies investigating the effect of junction density as one of the independent variables in a multiple regression model, one reports that junction density significantly increases crashes whereas the other reports significant decreases. The remaining three studies reveal that:

- The number of crashes involving cyclists increases if the density of signalised intersections increases
- The number of child pedestrian casualty crashes on weekends decrease with increasing junction density (probably the result of lower demand)
- Increased intersection density results in a significant decrease in pedestrian crashes.

Overall the studies reveal mixed results. Although increased junction density appears to reduce certain crash types, the studies seem to suggest that increased junction density leads to an overall increase in the number of crashes. For pedestrians, increased junction density improves accessibility

[2] (Elvik, Hoye, Vaa, & Sorensen, 2009)

and walkability and fewer pedestrian crashes whereas for cars and other road users increased junction density leads to more conflict potential (crash risk) and more crashes.

1.6 NOTES ON ANALYSIS METHODS

The effect of intersection/junction density has not been extensively studied or reported in scientific journals in Europe or the rest of the world. The studies that have been undertaken are generally based on statistical regression models using different sets of dependant and independent variables and resulting in incomparable results. Methodologically the studies vary in quality and although generally sound, certain assumptions and/or omissions weaken the applicability of the results. Exposure data (traffic volumes etc.) are often not corrected for. The results of the studies are site and condition specific which limits transferability of the results. The effect of junction density has not been systematically studied under varying conditions, for all road user groups and all crash and injury types.

2 Scientific overview

2.1 LITERATURE REVIEW

The literature review is based on the coded studies for the risk factor densely spaced junctions

2.1.1 Description of studies

5 studies were selected for coding on the basis of being the most recent, relevant (in terms of reported effects of junction density on road traffic crashes) and published in recognized scientific journals. All of these studies were coded. Two studies investigated crash frequency for all crashes (Wang and Huang, 2016 and Marshall et. al 2011), and one of these also investigated the relationship between junction density and crash severity (severe injury and fatal crashes, Marshall et. al 3011). Of the remaining studies one investigated the relationship between various land use factors (and junction density) and their effect on child pedestrian crashes (Dissanayakea et. al, 2009). Another study (Srinivas S. Pulugurtha and Vidya Thakur, 2015) compared crashes involving bicycles on roads with and without on-street cycle lanes and investigated the effect of signalized intersection density. The final study (Quistberg et. al, 2015) presented relationships between a large number of variables (including intersection density) and urban crashes involving pedestrians at intersections and mid-block.

Of the studies investigating the relationship between crash frequency and junction density (as one of a number of independent variables), the Wang and Huang study (2016) proposed a hierarchical (GLM) model which could be useful for road network planners. It establishes relationships between crashes and micro-level variables relevant to road sections and intersections and also crashes and network level variables. At the network level intersection density is found to marginally increase the expected number of crashes (1% with every unit increase). This affect is statistically significant. At the road level, access density negatively influences crashes (1,7% increase with every unit increase). The results of this study are very specific and the validity would need to be tested by applying the model on other road networks. Transferability may be an issue. Furthermore, the variables selected at both street and Traffic Analysis Zone (TAZ) level seem somewhat arbitrary and further investigation may be needed to determine if other variables are not more suited.

The paper by Marshall et. al. (2011) presents Negative Binomial regression models that assess the effect of streets and street networks on three levels of crashes (all; severe injury only and fatal only). The study evaluates a number of independent variables (although is not explicit in why only these were selected and others omitted) and selects 7 as being significant predictors across all crash categories. The significant independent variables are intersection density (topic of this synopsis); link to node ratio; no of lanes; bisecting/adjacent highways; distance from city centre; percentage streets with on-street parking and percentage of streets with bike lanes. The major statistically significant tested findings are that increasing junction density relate to decreasing crash number when compared to a reference situation (for example a 56% increase in junction density leads to a reduction of almost 16% in all crashes; 21% in severe crashes and 43%in fatal crashes). Compared to a reference situation, lower junction densities are associated with an increase in crashes across all crash categories. Higher link to node ratios were shown to relate to increased crashes as was the number of lanes.

Dissanayakea et. al (2009) investigated the effect of junction density on crashes among specific road user groups. They found that secondary retail and high density residential land use are associated with child pedestrian injuries. Junction density does not appear to materially affect child pedestrian injuries, the only effect is a decrease in slight injury crashes over weekends (probably due to lower volumes of child pedestrians and/or traffic). A weakness of the study is that it does not correct for exposure (in pedestrian and vehicular volumes). Furthermore, the scope of the study is fairly limited (restricted to one area of the UK) meaning that transferability is questionable.

Pulugurtha and Thakur (2015) evaluated the effectiveness of on-street bicycle lane in reducing crashes involving bicyclists on urban roads. As part of this research they assessed the role of network characteristics (including the number of driveways, unsignalised approaches and signalised intersections per unit distance) on risk to bicyclists. Data for thirty-six segments with on-street bicycle lane and twenty-six segments without on-street bicycle lane in the city of Charlotte, North Carolina were analysed. The authors developed Negative Binomial regression models which revealed that bicyclists are three to four times at higher risk (based on traffic conditions) on segments without on-street bicycle lane when compared to segments with on-street bicycle lane. An increase in annual motor vehicle miles travelled (MVMT) and the number of signalised intersections per mile increased the number of bicycle crashes. Along with a number of other variables they found that the density of signalised intersections has a significantly increases the number of bicycle crashes (a unit increase in density results in nearly 20% more bicycle crashes). The study does not correct for the exposure of bicycle use although it does do so for vehicle use (in terms of vehicle miles travelled).

Quistberg et al (2015) studied modifiable risk and protective factors of pedestrian crashes using micro and macro-level data (from location type, intersection control, speed limits and other physical characteristics to residential density, fast food outlet density, bus ridership data etc). The study finds among others that traffic signals have a significantly higher number of crashes than other control types; that pedestrian collisions are double at locations with marked crosswalks than locations without and that increased intersection density reduces crashes involving pedestrians. The results can be useful in identifying and prioritising locations that have a high risk for pedestrian crashes. Spatiotemporal data on the built environment is a good source and should be explored more often in this type of study. As with a number of the other studies, the effect of traffic volume is not corrected for and hence logical effects have been found (e.g. that signalised junctions have more crashes simply because there is more traffic with more conflicts).

To summarise, Table 1 provides an overview of the main features of coded studies (sample, method, outcome and results).

Table 1 Description of coded studies

Author(s), Year	Sample and study design	Method of analysis	Outcome indicator	Main result
Wang and Huang (2016)	Road network comprising 346 segments and 298 junctions making up 208 TAZ. Crash and traffic volume data over 3 years. Observational, cross-sectional study incorporating regression modelling	Bayesian hierarchal joint model	Number of crashes	Increased intersection density relates to increased crashes (1% per unit increase in density)

Marshall et al (2011)	230000crashes over 11 years in 24 Californian (USA) cities comparing street network layouts and relationship with crashes. Observational and cross-sectional study	NB models	Number of crashes Number of severe and fatal crashes	Increased junction density relates to a reduced crashes (56% increase in density relates to 16% fewer crashes and 42% fewer fatal crashes)
Dissanayake a et. al (2009)	522 crashes involving child pedestrians in 11 of 12 wards in Newcastle (UK), 90 of which 90 killed or seriously injured (KS) over 2000–2005, Observational and cross sectional study incorporating GLM techniques	Poisson and NB models	Number of child pedestrian crashes Number of child pedestrian KSI crashes	Junction density has no significant effect on child pedestrian crashes other than on weekends where increased density relates to a reduction in child pedestrian crashes (IRR 0,60)
Pulugurtha and Thakur (2015)	**3460 crashes in 3 years ((55 bicycle) on 55,68km** roadway without bicycle lane and 2175 crashes (13 bicycle) on 59,2km roadway with bicycle lane in Charlotte, North Carolina, USA. Observational and cross-sectional study incorporating GLM techniques	Linear, Poisson; Negative binomial	Number crashes and number of bicycle crashes per year	Density of signalised intersections significantly relates to an increase in the number of crashes involving bicycles up to (20% increase per unit increase in density)
Quistberg et al (2015)	15,363 intersections and 21,997 mid-block locations in Seattle with 2695 pedestrian collisions (65% at intersections and 35% at mid-blocks between 2007-2013). Observational and cross sectional study incorporating regression modelling	Poisson models	Number of crashes involving pedestrians	Increased intersection density relates to a decrease in the number of pedestrian crashes (IRR of 0.64)

* 1: no injury, 2: possible injury, 3: non incapacitating injury, 4: incapacitating injury, 5: fatal

2.2 ANALYSIS METHODS AND RESULTS

2.2.1 Introduction

The effects of increased junction density can be summarized as follows:

- 1 study showing a decrease in the number of child pedestrian crashes
- 1 study with a significant decrease in the overall number of crashes
- 1 study with a significant decrease in the number of pedestrian crashes
- 1 study with a significant increase in the overall number of crashes
- 1 study with a significant increase in bicycle crashes

Table 1 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 1 Description of coded studies

Author(s), Year	Country and period covered	Method of analysis	Outcome indicator	Effect on safety	Exposure taken into account	Main result
Wang and Huang (2016)	USA (2005-2007)	Bayesian hierarchal joint model	Number of crashes	↗	Yes	Increased intersection density leads relates to increased crashes (1% per unit increase in density)

Marshall et al (2011)	24 Californian cites (USA (1997-2007)	NB models	Number of crashes Number of severe and fatal crashes	↘	Yes	Increased junction density lead relates to a significant reduction in crashes (56% increase in density relates to 16% fewer crashes and 42% fewer fatal crashes)
Dissanayake a et. al (2009)	UK, 2000-2005	Poisson and NB models	Number of child pedestrian crashes Number of child pedestrian KSI crashes	_	No	Junction density has no significant effect on child pedestrian crashes other than on weekends where increased density significantly relates to a reduction in child pedestrian crashes (IRR 0,60)
Pulugurtha and Thakur (2015)	Charlotte, North Carolina, USA. (2008-2010)	Linear, Poisson; Negative binomial	Number crashes and number of bicycle crashes per year	↗	Not bicycle volumes	Density of signalised intersections relates to an increase in the number of crashes involving bicycles up to (20% increase per unit increase in density)
Quistberg et al (2015)	Seattle, USA(2007-2013	Poisson models	Number of crashes involving pedestrians	↘	Partially, using a proxy variable	Increased intersection density decreases relates to a decrease of pedestrian crashes (IRR of 0.64)

* 1: no injury, 2: possible injury, 3: non incapacitating injury, 4: incapacitating injury, 5: fatal

The results of the coded studies are mixed. Furthermore, the effects are based on predominantly multiple regressions using different sets of variables and different models whereby the results do not lend themselves for meta-analysis.

2.2.2 Overall estimate for accident severity

Not all of the coded studies correct for exposure and the estimates are subject to different models with different sets of dependant and independent variables. Therefore the estimates are not directly comparable. Overall (based on all crashes) the studies seem to suggest that increased junction density leads to increased crashes. However, for pedestrians, increased junction density improves accessibility and walkability and may reduce pedestrian crashes.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature search aimed at identifying the highest quality and most recent studies for quantifying the relationship between junction density and crash occurrence (number of crashes) and crash severity. Therefore the document search strategy was primarily aimed at studies undertaken in Europe and published in recognized scientific journals and publications. Failing that, the search fell back on older studies and/or studies from other parts of the world but with the provision that these were published in recognized scientific publications. The Scopus and TRID databases were searched in the formal literature search.. All searches were filtered on English results only. The search was done in 2016.

To select papers relating to road safety in Scopus, the following query was used: ((road and casualt*) or (road and injur*) or (road and accident*) or (road and crash*) or (traffic and injur*) or (traffic and casualt*) or (traffic and accident*) or (traffic and crash*)).

To select papers relating to road safety in TRID, the following query is used: (collision* or crash* or accident* or injur* or casualt*) AND (traffic or road).[3]

The aforementioned queries were combined with a query to select papers relating to the risk factor densely spaced junctions: ((intersection and density) or (intersection and spacing) or (junction and density) or (junction and spacing))

These queries were combined in Scopus and TRID to search for literature about the risk factor densely spaced junction. To distinguish literature from Europe and Worldwide, the results were loaded into Mendeley, where the following query was used to identify literature from Europe: (Italy or Ireland or Hungary or Greece or Germany or France or Finland or Estonia or Denmark or Czech or Cyprus or Croatia or Bulgaria or Belgium or Austria or Scotland or England or Britain or United Kingdom or Sweden or Spain or Slovenia or Slovakia or Romania or Portugal or Poland or Netherlands or Malta or Luxembourg or Lithuania or Latvia).

The number of hits for Europe and Worldwide and for Scopus and TRID are presented in table 1.

Table 1 Literature search strategy

search no.	Region	Database	hits
#1	Europe	Scopus	24
#2	Europe	TRID	50
#3	Worldwide	Scopus	160
#4	Worldwide	TRID	246

3 The difference in the queries is due to differences in restrictions to the query length between the two sources.

Following the initial selection of relevant publications, a secondary selection of publications was made in Mendeley, sorting the initial publications on year and source. Only publications from trusted sources and most recent publications were selected with a maximum number of about 80. From this selection all abstracts were reviewed on relevance. From reviewing the abstracts a total of 14 publications were selected as the most promising. For 4 of these the full text version could not be retrieved and these were not considered further. The remaining 10 publications were reviewed and 5 of these were judged unsuitable for coding (specific effect not reported, topic not specifically addressed etc.).

The final studies selected for the topic junction density suggest that although this topic has been studied in some depth, the study methodologies and subsequent results are diverse and mixed. No meta-analyses were found on this topic and the literature review reveal that the results of the selected five studies do not lend themselves for inclusion in a meta-analysis. The majority of these are based on multiple regression models using different dependant and independent variables and with widely varying outcomes.

3.2 LIST OF STUDIES

A detailed list of studies considered (and of which the first 5 were selected for coding) is listed in this paragraph.

3.2.1 Coded studies

Dissanayake, D., Aryaija, J., & Wedagama, D. M. P. (2009). Modelling the effects of land use and temporal factors on child pedestrian casualties. *Accident; Analysis and Prevention*, *41*(5), 1016–24. http://doi.org/10.1016/j.aap.2009.06.015

Marshall, W. E., & Garrick, N. W. (2011). Does street network design affect traffic safety? *Accident Analysis & Prevention*, *43*(3), pp 769–781. http://doi.org/10.1016/j.aap.2010.10.024

Pulugurtha, S. S., & Thakur, V. (2015). Evaluating the effectiveness of on-street bicycle lane and assessing risk to bicyclists in Charlotte, North Carolina. *Accident Analysis & Prevention*, *76*, pp 34–41. http://doi.org/10.1016/j.aap.2014.12.020

Quistberg, D. A., Howard, E. J., Ebel, B. E., Moudon, A. V, Saelens, B. E., Hurvitz, P. M., … Rivara, F. P. (2015). Multilevel models for evaluating the risk of pedestrian–motor vehicle collisions at intersections and mid-blocks. *Accident Analysis & Prevention*, *84*, pp 99–111. http://doi.org/10.1016/j.aap.2015.08.013

Wang, J., & Huang, H. (2016). Road network safety evaluation using Bayesian hierarchical joint model. *Accident Analysis & Prevention*, *90*, 152–158. http://doi.org/10.1016/j.aap.2016.02.018

3.2.2 Other considered studies

Ferreira, S., & Couto, A. (2011). Urban Road Planning: A Safety Perspective. In *ICTIS 2011* (pp. 622–628). Reston, VA: American Society of Civil Engineers. http://doi.org/10.1061/41177(415)79

Ferreira, S., & Couto, A. (2015). A probabilistic approach towards a crash risk assessment of urban segments. *Transportation Research Part C: Emerging Technologies*, *50*, 97–105. http://doi.org/10.1016/j.trc.2014.09.012

Green, J., Muir, H., & Maher, M. (2011). Child pedestrian casualties and deprivation. *Accident; Analysis and Prevention*, *43*(3), 714–23. http://doi.org/10.1016/j.aap.2010.10.016

Ha, H.-H., & Thill, J.-C. (2011). Analysis of traffic hazard intensity: A spatial epidemiology case study of urban pedestrians. *Computers, Environment and Urban Systems*, *35*(3), 230–240. http://doi.org/10.1016/j.compenvurbsys.2010.12.004

Ivan, J. N., Wang, C., & Bernardo, N. R. (2000). Explaining two-lane highway crash rates using land use and hourly exposure. *Accident Analysis and Prevention*, *32*(6), 787–795. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0034326936&partnerID=tZOtx3y1

Kaplan, S., & Giacomo Prato, C. (2015). A Spatial Analysis of Land Use and Network Effects on Frequency and Severity of Cyclist–Motorist Crashes in the Copenhagen Region. *Traffic Injury Prevention*, *16*(7), pp 724–731. Retrieved from http://dx.doi.org/10.1080/15389588.2014.1003818

Kiec, M., Tracz, M., & Gaca, S. (2012). Design of Cross-Section on Roads Through Built-Up Areas. *Archives of Civil Engineering*, *58*(3), 243–257. http://doi.org/10.2478/v.10169-012-0015-y

Prinsloo, B., & Goudanas, C. (2003). Development of a crash prediction model for rural roads in NSW. In *Proceedings - Conference of the Australian Road Research Board* (Vol. 21, pp. 57–65). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-1842612450&partnerID=tZOtx3y1

Xie, K., Wang, X., Ozbay, K., & Yang, H. (2014). Crash frequency modeling for signalized intersections in a high-density urban road network. *Analytic Methods in Accident Research*, *2*, 39–51. http://doi.org/10.1016/j.amar.2014.06.001

Synopsis 17: Alignment deficiencies - High Grade

1 Summary

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NTUA, August 2016

COLOUR CODE: YELLOW

Explanation: The presence of steep uphill or downhill vertical grades can contribute to the occurrence of accidents, to increased accident severity and injury severities, and incidents of speeding. The exact amount of the effect is unclear, as this varies between studies, with few also bordering on statistical significance.

KEYWORDS:

Vertical grade; high grade; slope; vertical alignment; road accident;

1.1 ABSTRACT

The presence of steep uphill or downhill vertical grades in the road geometry, either alone or combined with horizontal curves, affects the level of road safety. This translates not only to induced accidents (both absolute numbers and frequencies), but also to increased injury severity and speeding which has been proven to lead to accidents. A vote-count analysis was performed to capture these overall effects for high grade.

1.2 BACKGROUND

1.2.1 Definition of high grade

The risk factor is used with a number of descriptions: Vertical alignment/grade, high grade/gradient, slope, uphill/downhill geometrical design etc. It is usually a numeric number measured in percentiles, though some studies might choose to categorise it (eg. “flat area”, “low uphill”, “high uphill”, “low downhill”, “high downhill”). What happens in most studies is a threshold is selected. It is up to the individual research team to determine a value for what they consider an unusually high grade and to treat it as a risk factor, for instance, grades higher than 5% on motorways.

1.2.2 How do high grades affect road safety?

Although it is not generally discussed in the studies, or tackled alone as a factor, it is understood that high grades increase or decrease vehicle acceleration and speed, and thus make a vehicle harder to control precisely, especially if it has a lot of inertia and increased handling difficulty, such as heavy goods vehicles (trucks). This especially applies in cases where high grade or grade variations coincide with sharp horizontal curves, which is why a number of studies examine this combination of risk factors. Moreover, it is understood that the presence of grades may influence driver behaviour, inducing additional acceleration or deceleration, even to the point of overcompensation that can lead to differentiation of velocities which is a well-known accident risk factor. Finally, it is worth noting that steep grades are often considered implausible in design, and all design manuals recommend avoiding or keeping minimal the use of steep slopes.

1.2.3 Which safety outcomes are affected by high grade?

The reviewed studies focus on various outcomes. In several studies, the main focus is estimating the number of accidents, either absolutely or over time (accident frequency) that occur due to high grades. In addition to this, some studies investigate accident or injury severity. Finally, two single studies investigate different outcomes: speeding as a secondary risk factor and driver fault in the case of crashes.

1.2.4 How is the effect of high grade on road safety studied?

The international literature has examined a multitude of different approaches and ways to study the effect of high grade. This is due to the fact that this particular risk factor is mostly examined alongside others and not by itself, and its examination is adjusted to the models selected every time.

The threshold approach mentioned above is the most common method, which categorizes all grades into “high” and “not high”. There are also categorical and continuous numeric approaches. The coded studies are observational, with both case-control and cross-sectional designs. Some of them focus on specific areas, such as motorways or ramps, while others conduct aggregate analyses.

1.3 OVERVIEW OF RESULTS

The effect of high grade on road safety is mostly detrimental, namely increasing accident risk and severity, but also somewhat varied. Usually when high grades are involved, the various study findings link them to increased accident frequency or injury severity. There have been two studies that deviated from this trend. The first one found that large vertical alignment grade (>10%) has a marginally statistically significant effect on reducing the speed of vehicles, providing a beneficial impact on road safety. The second one discovered an increase in crash frequency for about half of the segments examined, while the others had a decrease, both for a corresponding one unit of increase in vertical grades. There have also been cases where no statistically significant effect was found for this specific risk factor on road safety.

1.3.1 Transferability

Coded studies are based on data from various countries around the globe, though the United States and China have increased representation, making the findings somewhat transferable (since no studies were found from Europe). All studies concerned themselves with the entirety of motor vehicles for road accidents, combining cars, PTWs, LGVs, HGVs and buses without differentiating for different road users.

1.3.2 Notes on analysis methods

The risk factor of high grade is rarely studied in isolation. The prevalent trend is that high grade is studied as a secondary characteristic of road geometry, which is mostly considered alongside another main risk factor (e.g. traffic flow) and not by itself. This means that the study designs are not usually tailored towards capturing the effect of that particular risk factor. There is a lot of room for investigating different road user groups. Finally, there have been a number of different modeling approaches and different indicators used in the coded studies, ranging from ordered logit and probit models to Poisson, negative regression models and more unusual models such as the ordered response fractional split model. To summarize, given that there is a decent amount of relevant studies with a somewhat similar conclusion, the transferability of the findings is possible.

2 Scientific overview

2.1 ANALYSIS OF METHODS AND PRESENTATION OF RESULTS

2.1.1 Analysis of study designs and methods

After appropriate use of various search tools and databases, thirteen (13) high quality studies were selected and coded for the risk factor of high grade. Six of the studies investigated accident frequency (Ahmed et al., 2011, Agbelie, 2016, Chang, 2005, Fu et al., 2011, Poch and Mannering, 1996, Yu and Abdel-Aty, 2013), three examined accident or injury severity (Choi et al., 2011, Wang et al., 2009, Xing et al., 2015), two examined crash numbers (Montella and Imbriani, 2015, Wu et al., 2014), one examined increased speeding groups (Eluru et al., 2013) and finally the last one concerned driver fault (Harootunian et al., 2014).

In order to examine the relationship between high grade and outcome indicators, all studies deployed multivariate statistical models (i.e. negative binomial, Poisson, etc.) as a method of examining the topic. As mentioned before, other independent variables were present as well, with some models controlling for them and others studying them independently. For instance, apart from high grade, Agbelie (2016) controlled for area type, presence of rolling terain, presence of ice, time of day, truck traffic, stop signs, lane width and median width in the model.

Four out of the six studies which examine accident frequency indicate a direct correlation between high grade and accident frequency, while the other two (Agbelie, 2016, Chang, 2005) indicated mixed results. They utilized forms of Poisson and negative binomial models. All three studies examining accident or injury severity (Choi et al., 2011, Wang et al., 2009, Xing et al., 2015) conclude that gradients different than level ground are significantly associated with increased injury severity. Crash numbers were found to be completely (Montella and Imbriani, 2015) or partially (Wu et al., 2014) directly correlated with high grades, along with driver fault (Harootunian et al., 2014). Speeding vehicle numbers were found to be reduced, however, in steep grades (more than 10%) (Eluru et al., 2013).

As explained above, most coded studies use the threshold approach, i.e. setting a certain percentage as a limit between high and low grade. Two studies (Ahmed et al., 2011, Yu and Abdel-Aty, 2013) use a more detailed categorical approach, clustering the grades into groups (i.e. 0%-2%, 2%-4% etc.), while two use a continuous numerical variable approach (Choi et al., 2011, Xing et al., 2015). Another study has measured the average grade on continuous long descending road segments (Fu et al., 2011), while another has weighed the average grade with the length of the corresponding road segment with some adjustments (Montella and Imbriani, 2015).

An overview of the main features of the coded studies (sample, method, outcome and results) is illustrated on Table 2 of the supporting document.

2.1.2 Limitations

Some limitations can be arguably found in the current literature for the effects of high grade on road safety. The first would be the aforementioned threshold approach, with the obvious limitation of categorizing all grades into “high” and “not high”, which means that in a threshold of 5%, a gradient of 5.01% is considered high and therefore inducing the particular risk factor while a gradient of 4.99%

is not. This might not reflect the real impact of road geometry. Additionally, the majority of studies do not differentiate between positive and negative grade (uphill and downhill), which again has considerably different impacts on driver and vehicle behavior.

2.2 ANALYSIS METHODS AND RESULTS

2.2.1 Introduction

The effects identified to result from higher grade can be summarized as follows:

- 3 studies with a significant increase on accident frequency
- 1 study with a significant increase on accident frequency on some road segments and a significant decrease on accident frequency on others
- 1 study with a significant increase on accident frequency for some grades and a significant decrease on accident frequency for others
- 1 study with a significant increase on accident frequency for some grades and a non-significant effect on accident frequency for others
- 1 study with a significant increase on accident numbers
- 1 study with partially a significant increase on accident numbers and partially a non-significant increase on accident numbers
- 3 studies with a significant increase on accident or injury severity
- 1 study with a significant decrease on speeding vehicles
- 1 study with a significant increase on driver fault

After the results were reviewed together in consideration of what type of analysis to conduct, the following points were observed:

a) There is an adequate number of studies that could support a meta-analysis, however;
b) Those studies have not used the same model for analysis but radically different ones.
c) There are many indicators, and even the most common ones are often not measured in the same way.
d) The sampling frames were quite different.

The complete detailed results from the coded studies appear on Table 3, which due to length is provided in the supporting document.

2.3 DESCRIPTION OF ANALYSIS CARRIED OUT

2.3.1 Vote-count analysis

After considering the previous points it was decided that a meta-analysis could not be carried out in order to find the overall estimate of high grade on accident frequency. Therefore the vote count analysis was completed. In vote count analyses, each study is given a vote for or against the risk-factor. The results are summarized in Table 1.

2.3.2 Overall estimate for road safety

On a basis of both study and effect numbers, it is apparent that the risk factor of high grade has an overall negative effect on road safety. However there are cases when its impact is inconclusive, or even has a beneficial effect, as has been shown on Table 2. The fact is that the majority of studies shows increased accident frequency, accident number, accident severity effects, while there are a few examples that affect road safety in a positive manner by reducing speeding vehicles. The variation between indicators, models, framing and general details between studies made the circumstances for conducting a meta-analysis inappropriate.

Outcome definition	Tested in number of studies	Result (number of studies)			Result (% of studies)			Result (number of effects)			Result (% of effects)		
		↑	-	↓	↑	-	↓	↑	-	↓	↑	-	↓
Accident frequency	6	5	1	-	83.3%	16.7%	-	24	15	1	60.00%	37.50%	2.50%
Accident numbers	2	1	1	-	50.0%	50.0%	-	27	4	-	96.43%	3.57%	-
Accident or injury severity	3	3	-	-	100.0%	-	-	4	-	-	100.00%	-	-
Speeding vehicles	1	-	-	1	-	-	100.0%	-	-	1	-	-	100.00%
Driver fault	1	1	-	-	100.0%	-	-	16	-	-	100.00%	-	-
Total studies N=13							Total effects n=92						

Table 1: Vote-count analysis results for high grade risk factor

2.4 CONCLUSION

The vote-count analysis carried out showed that high grade is associated with an increased risk of accident frequency and absolute accident numbers in the majority of cases. It is also related to an increased risk of accident injury and severity and driver fault at all times. However, there is a study to show that high grade leads to the macroscopic slowing down of vehicles, therefore indirectly affecting road safety positively. This leads to the assignment of the yellow colour code to high grade.

3 Supporting document

3.1 OVERVIEW OF CODED STUDIES

An overview of the main features of the coded studies (sample, method, outcome and results) is illustrated on Table 2.

#	Author(s), year, country	Sampling frame for accident classification	Method for high grade investigation	Outcome Indicator	Main Result
1	Agbelie, B. R.; 2016; USA	The random-parameters negative binomial model is demonstrated using detailed data from Washington State. The data consist of 21,069 highway segments in the year 2011, with 4.964 as a mean number of crashes.	Random parameter negative binomial model.	Accident frequency - Number of crashes per year [Slope (β coefficient)]	The sign of the vertical grade was positive indicating a positive correlation between vertical grade and accidents. However, the random parameter model specification indicates that vertical grades greater than 5% increase crash frequency for 58.46% of the highway segments, and decrease for 41.54% of the highway segments by 0.121 for one unit increase in vertical grades.
2	Ahmed, M., Huang, H., Abdel-Aty, M., Guevara, B.; 2011; USA	The study area was Colorado, USA, on road segments on a 20-mile freeway section of. Crash data for 6 years (2000–2005, N=1877 crashes), roadway geometry, traffic characteristics and weather information in addition to the effect of steep slopes and adverse weather of snow and dry seasons, were used in the investigation	Poisson, random effects and spatial effects models.	Accidents - Incidence Rate Ratio (IRR). [Slope (β coefficient)]	Results identified clear trends associated with the effect of slopes, i.e. the steeper the slope, the higher the crash risk; and segments with upgrade slope are safer than downgrades in the same slope range.
3	Chang L.-Y.; 2005; Taiwan	The National Freeway I in Taiwan was considered and 1997–1998 accident data from that area was analysed. N = 1338 accidents.	Poisson and negative regression models.	Accident frequency - Number of crashes per year [Slope (β coefficient)]	The estimated results indicate sections with severe uphill grade (3% or more) or descent grades have increased likelihood of accident occurrence, while level sections have reduced likelihood of accidents.
4	Choi, J., Kim, S., Heo, T., Lee, J.; 2011; South Korea	A total of 137 traffic crashes that occurred in 24 locations in South Korea on national roads were obtained from the national police department and analyzed in this research. Crash data during 2002 and 2003 were used for the analysis.	Ordinal Logistic Regression model.	Accident severity - Categorical [Slope (β coefficient)]	It was found that terrain type is actually one of the most critical variables and this finding was seen not only in crash occurrence models but also in crash cost models. Vertical grade has substantial impact on safety in mountainous terrain.
5	Eluru N., Chakour V., Chamberlain M., Miranda-Moreno L.F.; 2013;	Local area: 120 roads in Montreal boroughs. The database for speed data was compiled in Montreal urban region and consisted of two roadway facility types: (1) local roads and (2) arterials. The data was collected during	Use of the ordered response fractional split model, which is extended to capture the impact of	Speeding groups - The proportion of vehicles in each speed category for every hour. [Slope (β	Large vertical alignment grade (>10%) were found to be marginally statistically significant for reducing the speed of vehicles, providing a positive effect on road safety.

#	Author(s), year, country	Sampling frame for accident classification	Method for high grade investigation	Outcome Indicator	Main Result
	Canada	7 days during the period May–October 2009.	exogenous variables across the population and the influence of unobserved effects on the proportion variable.	coefficient)]	
6	Fu, R., Guo, Y., Yuan, W., Feng, H., Ma, Y.; 2011; China	In Western China, data from 1413 traffic accidents over an 85.43 km section of road were collected. Parameters such as the gradients in accident sites, and the average gradient in N km (N = 1, 2, 3, 4, 5) just prior to the accident sites as the profile parameter were established.	Exponential regression analysis.	Accident rate (a form of frequency - acc/year/km), which include a portion of damage only accidents, and all injuries and fatalities. [Pearson correlation coefficient]	The traffic accident rate at a specific section on continuous descending roads is related to the average gradient in 2–3 km sections just prior to the accident site and the traffic accident rate increases with the average gradient. Moreover, steep gradients alone do not always result in higher accident rates. It is the continuous long steep descending gradients rather than simply steep gradients that result in higher accident rates.
7	Harootunian, K., Lee, B.H.Y., Aultman-Hall, L.; 2014; USA	Crash data from Florida, Maine, Minnesota, and Nevada was analyzed to model fault using logistic regressions. A total of 1,632,194 accidents were investigated between 01/01/2007 and 31/12/2011.	Univariate and multivariate logistic regression models.	Driver fault for accident cause [Odds Ratio]	The presence of high grade on roads increases faults of accidents at all cases analysed.
8	Montella, A., Imbriani, L.L.; 2015; Italy	Crash data were collected through analysis of police reports and were integrated with detailed site inspections for the years 2007–2011. Average annual daily traffic (AADT) data were provided by the motorway management agency for the same period. They are disaggregated for each carriageway and for each section between successive interchanges.	Generalised linear model with negative binomial error structure.	Crashes by category (Total, single-vehicle run-off-road, other single vehicle, multi-vehicle, daytime, nighttime, non-rainy, rainy, dry pavement, wet pavement, property damage only, slight injury, severe and fatal)	Study results show that geometric design consistency has a significant effect on safety of rural motorways. Furthermore, greater longitudinal downgrades and upgrades significantly increase crash frequency and the safety effect is higher on horizontal curves than on tangents.
9	Poch, M., Mannering, F.; 1996; USA	This study was conducted using 7 year accident histories from 63 intersections in Bellevue, Washington (all of which were targeted for operational improvements).	Negative binomial regression .	Accident frequency - Number of crashes at intersection approaches [Slope (β coefficient)]	In general, an uphill or downhill grade greater than 5% on approach increase the freqency of accidents in intersections, along with sight-distance restrictions, horizontal curves and large gradients.

#	Author(s), year, country	Sampling frame for accident classification	Method for high grade investigation	Outcome Indicator	Main Result
10	Wang Z., Chen H., Jian J.; 2009; USA	Crash data and roadway information were collected at 231 selected freeway exit segments in the State of Florida. N = 10946 accidents.	Ordered probit model.	Injury severity - Categorical [Slope (β coefficient)]	Gradients different than level ground are significantly associated with increased injury severity.
11	Wu, W. Q., Wang, W., Li, Z. B., Liu, P., & Wang, Y.; 2014; China	Region: 32 sections of exit ramps on the Guangshen freeway in China. The freeway has a total length of 98 km and is located in the southern part of China. Four-year crash data at exit ramps were collected for modeling.	4 models: General Linear Model, Generalized Estimate Equation with three variations: autoregressive, exchangeable and unstructured.	Crashes on ramps; average or per year, depending on the model [Slope (β coefficient)]	Presence of longitudinal grade were sometimes not statistically significant, but at other times they appeared to have a negative effect on road safety.
12	Xing Y., Lu J., Wang C.; 2015; China	The traffic accident data was obtained from the Shanghai Transport and Port Authority. The study area consisted of river crossing tunnels in Shanghai. The driver, environmental, vehicle and tunnel characteristics of 508 single-vehicle accidents in 2011 were examined by an ordered logit model.	Ordered logit model.	Accident severity - Categorical [Odds ratio]	High grade was found to increase accident severity.
13	Yu, R., & Abdel-Aty, M.; 2013; USA	Data from a 15-mile montainous geometry motorway (steep slopes up to 7 %) and adverse weather conditions. Traffic data aggregated to 5-min intervals. Disaggregate model based on 1 year of accident data; aggregate model based on 5 years of accident data.	Bivariate Poisson-lognormal model.	Accident frequency - Modelled separately for single- and multi-vehicle accidents [Slope (β coefficient)]	A steeper slope is associated with a higher single vehicle crash risk, and downgrade slopes are relatively more hazardous than corresponding upgrades with the same slope ranges.

Table 2: Description of coded studies for high grade

3.2 IDENTIFYING RELEVANT STUDIES

Risk factor: gradient (high grade)

3.1.1 Literature search strategy

The literature search was conducted in Science Direct (Scopus), and the main search terms were variations of *grade/gradient, road* and *(vertical) alignment*, limited to studies published after 1990 in the English or French language. The search focused on hits in the titles, abstracts and key words of journal articles and reports. Titles and abstracts were screened during the search, and studies of potential relevance were screened full-text to assess relevance.

Database: Scopus **Date:** 23rd of March 2016

search no.	search terms / operators / combined queries	hits
#1	"grade" OR "gradient"	
#2	AND (“road” OR “vertical alignment” OR “alignment”)	2525
#3	AND (“road safety” OR “traffic accident” OR “road crash” OR "road accident" OR "risk")	179
	All years	187

Database: TRID (trid.trb.org) **Date:** 23rd of March 2016

search no.	search terms / operators / combined queries	hits
#1	Road gradient crash risk	25
	All years	32

Database: Science Direct **Date:** 23rd of March 2016

search no.	search terms / operators / combined queries	hits
#1	"grade" OR "gradient"	
#2	AND (“road” OR “vertical alignment” OR “alignment” OR “road safety” OR “traffic accident” OR “road crash” OR "road accident" OR "risk")	45

Limitations/ Exclusions:

- Search field: TITLE-ABS-KEY
- published: 1990 to current
- Document Type: ALL
- Source type: Journals or Conference Proceedings
- Subject Area: Engineering
- Language: English or French

Results Literature Search

Database	Hits
Scopus (remaining papers after limitations/exclusions)	179
TRID	25
Science Direct	45
Total number of studies to screen title/ abstract	264

3.3 SCREENING

The abstracts of relevant studies from the initial literature search results were examined to narrow the scope and to detect studies that would be more appropriate at a first stage. Those abstracts give hints as to whether the full text warrants close examination for coding and inclusion in the project.

Total number of studies to screen title/ abstract	264
-De-duplication	0
-Not relevant studies excluded	0
-Studies with no risk estimates excluded	0
Remaining studies	29
Not clear (full-text is needed)	13
Studies to obtain full-texts	42

3.4 ELIGIBILITY

Total number of studies to screen full-text	42
Full-text could be obtained	42
Reference list examined Y/N	YES (no additional papers)
Eligible papers prioritized	13

3.5 PRIORITIZING CODING

During the previous steps 42 studies were detected that could be appropriate for the scope of this synopsis. However, since that number was large, and coding time was finite, there was a final selection process in order to determine the best studies for the analysis. The process was conducted via prioritizing, based on the following criteria:

- Prioritizing Step A: meta-analysis first
- Prioritizing Step B: studies dedicated on this risk factor over studies with multiple risk factors
- Prioritizing Step C: journal papers first
- Prioritizing step D: studies published more recently
- Prioritizing Step E: studies from Europe

3.6 QUANTIFIED STUDY RESULTS FROM CODING

Below follows Table 3, which contains detailed results from the coded studies, as they were quantified in the vote-count analysis.

#	Author(s); Year; Country;	Outcome indicator	Quantitative estimate	Effect on road safety risk
1	Agbelie, B. R.; 2016; USA	Number of crashes per year [Slope]	β=0.0005, t-test=33.238, p=0.0000 with 95% sig.lvl.	↑
2	Ahmed, M., Huang, H., Abdel-Aty, M., Guevara, B.; 2011; USA	Crashes - Incidence Rate Ratio - Poisson model [Slope]	Grade Group [1] to [8]: β=-1.302, CI [95%]=[-1.538,-1.072]	↑
			Grade Group [2] to [8]: β=-0.855, CI [95%]=[-1.026,-0.685]	↑
			Grade Group [3] to [8]: β=-0.786, CI [95%]=[-0.949,-0.617]	↑
			Grade Group [4] to [8]: β=-0.530, CI [95%]=[-0.735,-0.328]	↑
			Grade Group [5] to [8]: β=-1.193, CI [95%]=[-1.421,-0.981]	↑
			Grade Group [6] to [8]: β=-0.888, CI [95%]=[-1.084,-0.704]	↑
			Grade Group [7] to [8]: β=-0.698, CI [95%]=[-0.884,-0.515]	↑
		Crashes - Incidence Rate Ratio - Random effects model [Slope]	Grade Group [1] to [8]: β=-1.287, CI [95%]=[-1.797,-0.778]	↑
			Grade Group [2] to [8]: β=-0.870, CI [95%]=[-1.322,-0.422]	↑
			Grade Group [3] to [8]: β=-0.907, CI [95%]=[-1.285,-0.516]	↑
			Grade Group [4] to [8]: β=-0.297, CI [95%]=[-0.845,0.277]	-
			Grade Group [5] to [8]: β=-1.167, CI [95%]=[-1.674,-0.657]	↑
			Grade Group [6] to [8]: β=-0.857, CI [95%]=[-1.322,-0.386]	↑
			Grade Group [7] to [8]: β=-0.672, CI [95%]=[-1.175,-0.185]	↑
		Crashes - Incidence Rate Ratio - Spatial effects model [Slope]	Grade Group [1] to [8]: β=-1.041, CI [95%]=[-1.950,-0.097]	↑
			Grade Group [2] to [8]: β=-0.458, CI [95%]=[-1.400,0.534]	-
			Grade Group [3] to [8]: β=-0.316, CI [95%]=[-1.251,0.679]	-
			Grade Group [4] to [8]: β=0.2370, CI [95%]=[-0.745,1.286]	-
			Grade Group [5] to [8]: β=-0.663, CI [95%]=[-1.374,0.047]	-
			Grade Group [6] to [8]: β=-0.434, CI [95%]=[-1.095,0.244]	-
			Grade Group [7] to [8]: β=-0.281, CI [95%]=[-0.886,0.342]	-
3	Chang L.-Y.; 2005; Taiwan	Number of crashes per year [Slope]	level indicator: β=-0.1610, t-test=-1.64 with 95% sig.lvl.	↓
			severe upgrade indicator: β=0.3530, t-test=-1.76 with 95% sig.lvl.	↑
			β=-0.0640, t-test=-1.46 with 95% sig.lvl.	-
4	Choi, J., Kim, S., Heo, T., Lee, J.; 2011; South Korea	Injury severity - Categorical [Slope]	β=0.1503, s.e.=0.1199, p=0.010	↑
		Injury severity - Categorical [Odds ratio]	OR=1.262, p=0.010	↑
5	Eluru N., Chakour V., Chamberlain M., Miranda-	Speeding groups (km/h) - Categorical [Slope]	β=-0.280, t-test=-1.62	↓

#	Author(s); Year; Country;	Outcome indicator	Quantitative estimate	Effect on road safety risk
	Moreno L.F.; 2013; Canada			
6	Fu, R., Guo, Y., Yuan, W., Feng, H., Ma, Y.; 2011; China	Accident rate (acc/year/km) [Correlation coefficient]	Localised gradient pecentage=0.385	-
			Average gradient within 1 km=0.584	-
			Average gradient within 2 km=0.643	↑
			Average gradient within 3 km=0.643	↑
			Average gradient within 4 km=0.572	-
			Average gradient within 5 km=0.500	-
7	Harootunian, K., Lee, B.H.Y., Aultman-Hall, L.; 2014; USA	Driver fault in a Single Vehicle Crash - Local Drivers [Odds ratio]	Florida: OR=1.240, p=0.950, CI [95%]=[1.200,1.580]	↑
			Maine: OR=1.830, p=0.950, CI [95%]=[1.770,1.900]	↑
			Minnesota: OR=1.260, p=0.950, CI [95%]=[1.220,1.300]	↑
			Nevada: OR=1.130, p=0.950, CI [95%]=[1.080,1.190]	↑
		Driver fault in a Single Vehicle Crash - Foreign Drivers [Odds ratio]	Florida: OR=1.400, p=0.950, CI [95%]=[1.230,1.580]	↑
			Maine: OR=1.700, p=0.950, CI [95%]=[1.500,2.000]	↑
			Minnesota: OR=1.300, p=0.950, CI [95%]=[1.170,1.440]	↑
			Nevada: OR=1.430, p=0.950, CI [95%]=[1.260,1.620]	↑
		Driver fault in a Two Vehicle Crash - Local Drivers [Odds ratio]	Florida: OR=0.970, p=0.950, CI [95%]=[0.950,0.980]	↑
			Maine: OR=1.000, p=0.950, CI [95%]=[0.970,1.030]	↑
			Minnesota: OR=1.030, p=0.950, CI [95%]=[1.010,1.040]	↑
			Nevada: OR=0.980, p=0.950, CI [95%]=[0.950,1.000]	↑
		Driver fault in a Two Vehicle Crash - Foreign Drivers [Odds ratio]	Florida: OR=1.000, p=0.950, CI [95%]=[0.910,1.070]	↑
			Maine: OR=1.020, p=0.950, CI [95%]=[0.910,1.140]	↑
			Minnesota: OR=0.990, p=0.950, CI [95%]=[0.940,1.060]	↑
			Nevada: OR=0.920, p=0.950, CI [95%]=[0.850,1.000]	↑
8	Montella, A., Imbriani, L.L.; 2015; Italy	Downhill Curve Total Crashes [Slope]	β=11.799, Model R^2 = 0.38	↑
		Downhill Curve Single-vehicle run-off-the-road Crashes [Slope]	β=7.128, Model R^2 = 0.57	↑
		Downhill Curve Multi-vehicle Crashes [Slope]	β=16.263, Model R^2 = 0.69	↑
		Downhill Curve Daytime Crashes [Slope]	β=12.838, Model R^2 = 0.36	↑
		Downhill Curve Nighttime Crashes [Slope]	β=9.397, Model R^2 = 0.40	↑
		Downhill Curve Non-Rainy Crashes [Slope]	β=12.764, Model R^2 = 0.36	↑
		Downhill Curve Rainy Crashes [Slope]	β=14.487, Model R^2 = 0.62	↑
		Downhill Curve Wet Pavement Crashes [Slope]	β=12.960, Model R^2 = 0.56	↑
		Downhill Curve Property damage	β=11.984, Model R^2 = 0.33	↑

#	Author(s); Year; Country;	Outcome indicator	Quantitative estimate	Effect on road safety risk
		only Crashes [Slope]		
		Downhill Curve Slight Injury Crashes [Slope]	β=5.833, Model R^2 = 0.62	↑
		Uphill Total Crashes [Slope]	β=7.529, Model R^2 = 0.39	↑
		Uphill Other single vehicle Crashes [Slope]	β=5.740, Model R^2 = 0.19	↑
		Uphill Multi-vehicle Crashes [Slope]	β=11.629, Model R^2 = 0.69	↑
		Uphill Daytime Crashes [Slope]	β=11.556, Model R^2 = 0.36	↑
		Uphill Non-Rainy Crashes [Slope]	β=6.918, Model R^2 = 0.36	↑
		Uphill Dry Pavement Crashes [Slope]	β=5.368, Model R^2 = 0.33	↑
		Uphill Property damage only Crashes [Slope]	β=12.394, Model R^2 = 0.33	↑
		Downhill Tangent Total Crashes [Slope]	β=5.827, Model R^2 = 0.72	↑
		Downhill Tangent Single-vehicle run-off-the-road Crashes [Slope]	β=9.149, Model R^2 = 0.64	↑
		Downhill Tangent Multi-vehicle Crashes [Slope]	β=8.280, Model R^2 = 0.93	↑
		Downhill Tangent Daytime Crashes [Slope]	β=9.414, Model R^2 = 0.66	↑
		Downhill Tangent Non-Rainy Crashes [Slope]	β=6.269, Model R^2 = 0.75	↑
		Downhill Tangent Rainy Crashes [Slope]	β=11.411, Model R^2 = 0.67	↑
		Downhill Tangent Dry Pavement Crashes [Slope]	β=5.250, Model R^2 = 0.72	↑
		Downhill Tangent Property damage only Crashes [Slope]	β=5.355, Model R^2 = 0.68	↑
		Downhill Tangent Slight Injury Crashes [Slope]	β=8.825, Model R^2 = 0.81	↑
9	Poch, M., Mannering, F.; 1996; USA	Rear-end accident frequency at intersections [Slope]	β=0.454, t-test=3.34	↑
		Angular accident frequency at intersections [Slope]	β=-0.251, t-test=-1.34	-
10	Wang Z., Chen H., Jian J.; 2009; USA	Injury severity - Categorical [Slope]	β=0.0813, s.e.=0.0280, p=0.0040, CI [95%]=[0.0264, 0.1362]	↑
11	Wu, W. Q., Wang, W., Li, Z. B., Liu, P., & Wang, Y.; 2014; China	Crashes on ramps on average [Slope]	GLM: β=0.1420, s.e.=0.1250, p=0.2590	-
		Crashes on ramps per year [Slope]	GLM: β=0.3230, s.e.=0.1440, p=0.0250	↑
			GLM with GEE - Exchangeable: β=0.3770, s.e.=0.2070	-
			GLM with GEE - Autoregressive: β=0.4020, s.e.=0.2090	-
			GLM with GEE - Unstructured: β=0.4450, s.e.=0.1820	-
12	Xing Y., Lu J., Wang C.; 2015; China	Injury severity - Categorical [Odds ratio]	OR=1.870, p=0.010, CI [95%]=[1.046, 3.343]	↑
13	Yu, R., & Abdel-Aty, M.; 2013; USA	Crash count [Slope]	Grade [0%-2%] compared to [(-6)%-(-8)%]: β=-1.770, s.e.=0.340, CI [95%]=[-2.430,-1.130]	↑
			Grade [2%-4%] compared to [(-6)%-(-8)%]: β=-0.520, s.e.=0.230, CI [95%]=[-0.980,-0.080]	↑
			Grade [4%-6%] compared to [(-6)%-(-8)%]: β=-0.5600, s.e.=0.160, CI [95%]=[-0.890,-0.240]	↑

#	Author(s); Year; Country;	Outcome indicator	Quantitative estimate	Effect on road safety risk
			Grade [6%-8%] compared to [(-6)%-(-8)%]: β=-0.170, s.e.=0.230, CI [95%]=[-0.630, 0.290]	-
			Grade [0%-(-2)%] compared to [(-6)%-(-8)%]: β=-1.580, s.e.=0.310, CI [95%]=[-2.200,-1.000]	↑
			Grade [(-2)%-(-4)%] compared to [(-6)%-(-8)%]: β=-0.360, s.e.=0.280, CI [95%]=[-0.920,0.180]	-
			Grade [(-4)%-(-6)%] compared to [(-6)%-(-8)%]: β=-0.400, s.e.=0.250, CI [95%]=[-0.900,0.100]	↑

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Synopsis 18: Presence of Tunnels

1 Summary

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COLOUR CODE: YELLOW

Explanation: The presence of tunnels can contribute to the occurrence of accidents; it can sometimes increase accident and injury severities; and also influence lateral control. The exact size of the effect is unclear, as this varies between studies, with few also bordering on statistical significance. There have also been some contradictory findings between studies.

KEYWORDS

tunnel length; tunnel lane number; tunnel accident; road safety; environmental factors;

1.1 ABSTRACT

Tunnels are widely used globally for ease of access and locomotion. However the presence of tunnels in road segments, either alone or combined with horizontal or vertical curves, affects the level of road safety. This translates not only to induced accidents, but also to increased injury severity and changes of the degree of lateral control which could be linked with accidents.

1.2 BACKGROUND

1.2.1 Definition of the presence tunnels

Since a very long time, tunnels have been used to increase mobility by circumventing obstacles, and they are used by a variety of users and vehicles. The presence of this risk factor exists in any road segment covered by a tunnel system (i.e. a closed construct made of hard materials, built almost always underground or underwater, and generally enclosed apart from an entrance in one end, an exit in the other, and, in more recent constructions, emergency exits in a perpendicular way). In the context of road safety research, it is usually encountered with a number of descriptions: tunnel length/dimensions, tunnel lane number, tunnel accident rates, etc. Within research studies about tunnels the tunnels are either simply noted as being present or absent, or specific details of the tunnel are considered e.g. length, number of lanes, slope.

1.2.2 How does the presence tunnels affect road safety?

It is generally understood that tunnels have a number of impacts on the road environment. They reduce visibility for vehicle drivers at all times, especially when their lighting and/or other signage is inadequate. On the other hand, intense sunlight or forgotten vehicle headlights when exiting the tunnel may induce increased visibility risk on opposite direction traffic. The presence of tunnels also imposes a level of discomfort to a certain percentage of individuals, due to the confined space they constitute. This limited space can also increase the arrival time of first responders at emergencies (for instance when an emergency lane is absent) and hinder communications, therefore increasing the chance of severe injuries occurring.

Furthermore, tunnel environments often present areas with potentially high environmental hazards, such as fire hazards (increased difficulty in extinguishing and ventilation), flood hazards (increased difficulty in water drainage), frost hazards (increased thawing times) or even debris from partial or even total collapse (admittedly a rare event). Finally, many drivers change their behaviour almost automatically when entering a tunnel, especially in higher slopes or curvatures. This results to unpredictable acceleration, speed and position variations within the traffic flow which are proven causes of road accidents.

1.2.3 Which safety outcomes are affected by the presence of tunnels?

The reviewed studies focus on various outcomes. In some studies, the main focus is estimating the number of accidents, either absolutely or over time (accident frequency) that occur due to tunnel presence. In addition to this, some studies investigate accident or injury severity. Finally, one simulation study investigates the impact of tunnels on lateral position control, driving speed and pathologic discomfort levels.

1.2.4 How is the effect of the presence tunnels on road safety studied?

The international literature has examined a variety of different approaches and ways to study the effect of tunnel presence. Often this particular risk factor is mostly examined alongside others and not by itself, and its examination is adjusted to the models selected to capture the entire situation for the given case.

The presence-or-absence approach mentioned above is the most common method, which categorizes road segments accordingly. Usually the tunnel segments coincide with the entirety of the tunnel length, but there have been studies when the portions were examined separately. In this situation, the two most frequently used approaches were the examination of the entirety of all tunnel kilometers together, regardless of how many tunnels this includes, or the analysis of every tunnel individually.

1.3 OVERVIEW OF RESULTS

The effects of the presence of tunnels tend to decrease the level of road safety, but are also quite varied. Usually the various study findings link tunnels to increased accident frequency or injury severity. One study found significantly increased accident frequency for both severe and non-severe accidents as tunnel length increases. Another study found increased single- and multi-vehicle accidents in tunnel segments.

With regard to position within the tunnel, accident and injury severity findings are unclear, as there have been two studies with contradictory results. One found increased injury severity for accidents that occurred on the entrance and exit segments of the tunnels when compared to those at the middle segments, while the second presented the opposite results. Both studies agreed on an increase in injury severity when the tunnel length increases. Furthermore, a third study found no statistically significant correlation between tunnel presence and accident severity of two-vehicle collisions with buses in non-highway areas.

Increases in tunnel lane number was found to increase accident frequency for non-severe accidents in one study, and accident severity in another. Finally, a single study found that the lateral control of drivers is influenced by the presence of tunnels. At the same time, average speed and course changes are reduced, which lead to the conclusion that drivers assume a more careful and conservative behaviour in the presence of tunnels.

1.3.1 Transferability

Coded studies are based on data from Italy, China and Canada. While this is a decent sample, there is still room for representation of other areas of the globe. Most studies examined all motor vehicles for road accidents, without differentiating for different road users. One study considered only accidents involving buses, and another used a driving simulator, but again there is room for other a greater variety of approaches.

1.3.2 Notes on analysis methods

The methodology applied for capturing the impact of tunnels on road safety varies considerably between studies. This is mainly in terms of the mathematical models utilised but also the outcomes evaluated as dependent variables.

What is more, the risk factor of tunnels is rarely studied in isolation. This means that the presence or other characteristics of tunnels are studied alongside another main risk factor (e.g. traffic flow). Consequently, the study designs are rarely completely tailored towards capturing the effect of that particular risk factor. There is some room for investigating different road user categories and/or other geographical regions. All aforementioned factors make the findings for tunnels transferable with caution.

2 Scientific overview

2.1 LITERATURE REVIEW

2.1.1 Analysis of study designs and methods

After appropriate use of various search tools and databases, six (6) high quality studies were selected and coded for the risk factor of the presence of tunnels. Three of the studies (Ma et al., 2016, Rahman et al., 2011, Xing et al., 2015) investigated accident or injury severity and a fourth (Caliendo et al., 2013) categorized accident frequency based on whether or not the accidents were severe, indirectly examining severity as well. Another study (Montella and Imbriani, 2015) examined accident number per category (single- and multi-vehicle accidents in tunnel segments) while the last one (Calvi et al., 2012) examined various behavioral variables such as lateral positioning control, driver speed and pathologic discomfort levels through simulation.

In order to examine the relationship between the various tunnel exposure and outcome indicators, all studies deployed multivariate statistical models (i.e. bivariate negative binomial, generalized ordered logit, etc.) as a method of examining the topic. Often other independent variables were present as well, with some models controlling for them and others studying them independently.

The first of the studies which examine accident or injury severity reports increased injury severity for accidents that occurred at the entrance and exit segments of the tunnels when compared to those at the middle segments (Ma et al., 2016). In stark contrast, the second relevant study (Xing et al., 2015) reports increased injury severity for accidents that occurred at the middle segments when compared to those at the entrance and exit segments of the tunnels. Furthermore, Rahman et al. (2011) found no statistically significant correlation between tunnel presence and the injury severity of two vehicle collisions with buses in non-highway areas.

When examining tunnels, a popular specific risk factor is tunnel length. Caliendo et al. (2013) found an increase of frequency for both accident categories (severe and non-severe accidents), while Xing et al. (2015) reported that extra-long tunnels (over 3000 m) increased accident severity. A different study (Montella and Imbriani, 2015) linked tunnel presence to increased numbers of specific accident types (single vehicle accidents that were not run-off road accidents and multi-vehicle accidents).

Another specific risk factor examined was the tunnel lane number in the tunnels. The number of lanes was found to increase the frequency of non-severe accidents (no statistically significant correlation was found with severe accidents) in one study (Caliendo et al., 2013) and to increase overall accident severity in the other (Xing et al., 2015).

With regard to various behavioral variables, the final study (Calvi et al., 2012) presented interested findings for exposure to the presence of tunnels using a driving simulator. With regard to lateral positioning control, findings show that drivers moved away laterally from the right tunnel wall (with reference to the traffic direction) when they drive inside the road tunnel and that they reduce their speed on a statistically significant level with reduced trajectory changes. Finally, pathologic discomfort was reported to be at a reduced level inside the tunnels (in three out of six at a statistically significant level). Those results are explained by the fact that drivers assume a more careful and conservative behaviour in the presence of tunnels. The tunnel environment provides a form of guidelines for driving, reducing driver stress and the need for trajectory corrections.

An overview of the main features of the coded studies (sample, method, outcome and results) is illustrated on Table 1.

Number	Author(s); Year; Country;	Sampling frame for tunnel study	Method for tunnel impact investigation	Outcome indicator	Main Result
1	Caliendo C., De Guglielmo M.L., Guida M.; 2013; Italy	260 Italian motorway were studied for 4 years. During the monitored period, crash data and traffic flow were collated. Some 2304 accidents were considered in this study, and the total length of the tunnels monitored was 303 km.	Bivariate negative binomial model	Accident frequency - Number of crashes per year (separated in severe and non-severe accidents) [Slope (β coefficient)]	Tunnel length increases the number of non-severe accidents (positive effect on safety) and the number of severe accidents (negative effect on safety). Lane number increases the number of non-severe accidents but has a non-significant effect on the number of severe accidents.
2	Calvi, A., De Blasiis, M. R., & Guattari, C.; 2012; Italy	Simulation tests were performed with a total length of the scenario was 8500 meters. The horizontal alignment had 6 tangents and 5 curves. Along the highway section there were 6 tunnels at different longitudinal positions with length ranged between 123 and 342 m.	Absolute difference & t-test	Lateral position, Driving speed, Pathologic discomfort [Absolute difference & t-test]	Drivers moved away laterally from right tunnel wall when they drive inside the road tunnel and slightly slow down. Trajectory corrections by the driver is definitely lower.
3	Ma Z., Chien S., Dong C., Hua D., Xu T.; 2016; China	Police-reported crash records for years 2003 and 2004 of four freeway tunnels were used. A total of 134 crash records were grouped according to the most severely injured individual of each crash.	Generalized Ordered Logit Model	Injury severity - Categorical [Slope (β coefficient)]	Accidents occurred near tunnel entrance/exit tend to be more severe than those occurred inside the tunnels. Tunnel length were also found positively affecting the likelihood of injury severity.
4	Montella, A., Imbriani, L.L.; 2015; Italy	Police report data and site inspections were combined for the years 2007–2011. AADT data were provided by the motorway management agency for the same period.	Generalised linear model with negative binomial error structure.	Crashes by various types (e.g. single-vehicle run-off-road, multi-vehicle, daytime, nighttime, and others)	The presence of tunnels has a significant effect on safety of rural motorways. Furthermore, greater longitudinal slopes significantly increase crash frequency and the safety effect is higher on horizontal curves than on tangents.
5	Rahman M.M., Kattan L., Tay R.; 2011; Canada	Bus crashes for the period 2000-2007 were extracted from the traffic crash data compiled by various police agencies. N=7967 two vehicle collisions.	Binary logistic regression model	Injury severity - Categorical [Slope (β coefficient)]	Tunnel presence was not affecting accident severity of two vehicle collisions with buses in non-highway areas in a statistically significant level.
6	Xing Y., Lu J., Wang C.; 2015; China	Tunnel accidents data considered in this study were extracted from a police database. The data contain 508 accident samples in 2011, and each sample contains driver information, vehicle characteristics, accident site, crash time and environmental conditions.	Ordered logit model	Injury severity - Categorical [Odds Ratio]	Extra long tunnels increase accident severity in relation to long tunnels. Accidents that occur in the middle of the tunnel are more severe than in the lengths before and after the entrance. High number of lanes increase severity.

Table 1: Description of coded studies for the presence of tunnels

2.1.2 Limitations

There are a few limitations in the current literature examining the effects of the presence of tunnels on road safety. The first is that very rarely can tunnel effects on drivers and vehicles be completely isolated, mainly because tunnels exist alongside other road geometry features such as horizontal and vertical curvature and slopes and other factors such as lighting. Additionally, there is no direct definition on the minimum length of a tunnel, which might induce some uncertainty about the effects of very small lengths (arches etc.) on road safety. Finally, there are unusual tunnel systems, such as Scandinavian ascending helix tunnels with high curvatures and slopes or shallow tunnels on mountainsides which have pillars on one side, a factor that radically changes lighting conditions. Such environments have not been taken into account in the research literature.

2.2 ANALYSIS METHODS AND RESULTS

2.2.1 Introduction

The effect of the presence of tunnels on road safety can be summarized as follows:

- 1 study with a significant increase on accident frequency (due to tunnel length for severe accidents and due to tunnel length and number of lanes for non-severe accidents)
- 1 study with a significant increase on accident numbers
- 2 studies with a significant increase on accident or injury severity (though disagreeing for the areas of the tunnel where this occurs)
- 1 study without a statistically significant correlation of accident or injury severity with tunnel presence
- 1 study with an influence of lateral control of drivers by the presence of tunnels. At the same time, average speed and trajectory changes were reduced

The complete detailed results from the coded studies appear on Table 2 which follows:

After the results were reviewed together, in possible consideration of a meta-analysis, the following points were observed:

a) There is an adequate number of studies, however;
b) Those studies have not used the same model for analysis but radically different ones.
c) There are different indicators, and even when they coincide they are not measured in the same way.
d) The sampling frames were quite different.

Number	Author(s); Year; Country;	Outcome indicator	Quantitative estimate	Effect on road safety risk
1	Caliendo C., De Guglielmo M.L., Guida M.; 2013; Italy	Number of non-severe accidents [Slope]	β=0.6575, s.e.=0.0715 with 95% sig.lvl.	↓
		Number of severe accidents [Slope]	β=0.4756, s.e.=0.0947 with 95% sig.lvl.	↑
2	Calvi, A., De Blasiis, M. R., & Guattari, C.; 2012; Italy	Driving speed - Average [Absolute difference]	Tunnel_1: Abs.Diff.=-3.100, t-test=1.63, p=0.1100	-
			Tunnel_2: Abs.Diff.=-6.200, t-test=2.57, p=0.0100	↓
			Tunnel_3: Abs.Diff.=-13.500, t-test=5.94, p<0.010	↓
			Tunnel_4: Abs.Diff.=-9.900, t-test=4.00, p<0.010	↓
			Tunnel_5: Abs.Diff.=-11.200, t-test=3.45, p<0.010	↓
			Tunnel_6: Abs.Diff.=-5.300, t-test=1.43, p=0.160	-
		Lateral position - Average [Absolute difference]	Tunnel_1: Abs.Diff.=0.520, t-test=6.68, p<0.010	↑
			Tunnel_2: Abs.Diff.=0.620, t-test=6.23, p<0.010	↑
			Tunnel_3: Abs.Diff.=0.290, t-test=2.77, p<0.010	↑
			Tunnel_4: Abs.Diff.=0.400, t-test=5.71, p<0.010	↑
			Tunnel_5: Abs.Diff.=0.280, t-test=6.12, p<0.010	↑
			Tunnel_6: Abs.Diff.=0.120, t-test=1.82, p=0.08	↑
		Pathologic discomfort - Average [Absolute difference]	Tunnel_1: Abs.Diff.=-2.100, t-test=1.69, p=0.1000	-
			Tunnel_2: Abs.Diff.=-5.800, t-test=2.86, p<0.010	↓
			Tunnel_3: Abs.Diff.=-13.500, t-test=4.35, p<0.010	↓
			Tunnel_4: Abs.Diff.=-1.500, t-test=1.07, p=0.2900	-
			Tunnel_5: Abs.Diff.=-8.200, t-test=2.44 p=0.020	↓
			Tunnel_6: Abs.Diff.=-7.600, t-test=3.05, p<0.010	↓
3	Ma Z., Chien S., Dong C., Hua D., Xu T.; 2016; China	Fatal Injury severity - Categorical [Slope]	Near entrance compared to middle of tunnel: β=-0.219, s.e.=1.241, p=0.016 with 95% sig.lvl.	↓
			Short tunnel: β=18.986, s.e.=1.580, p=0.000 with 95% sig.lvl.	↑
			Medium tunnel: β=20.545, s.e.=1.647, p=0.000 with 95% sig.lvl.	↑
			Long tunnel: β=21.887, s.e.=1.648, p=0.000 with 95% sig.lvl.	↑
		Injury severity - Categorical [Slope]	Near entrance compared to middle of tunnel: β=-0.496, s.e.=0.609, p=0.009 with 95% sig.lvl.	↓
			Short tunnel: β=17.431, s.e.=0.553, p=0.000 with 95% sig.lvl.	↑
			Medium tunnel: β=18.065, s.e.=0.456, p=0.000 with 95% sig.lvl.	↑
			Long tunnel: β=18.850, s.e.=0.005, p=0.000 with 95% sig.lvl.	↑
4	Montella, A., Imbriani, L.L.; 2015; Italy	Tunnel Curve Other Single vehicle Crashes [Slope]	β=0.762, Model R^2 = 0.19	↑
		Tunnel Curve Multi-vehicle Crashes [Slope]	β=0.690, Model R^2 = 0.69	↑
5	Rahman M.M., Kattan L., Tay R.; 2011; Canada	Injury severity - Categorical [Slope]	β=1.397, p=0.130 with 95% sig.lvl.	-
6	Xing Y., Lu J., Wang C.; 2015; China	Injury severity - Categorical [Odds ratio]	Tunnel length: OR=0.399, CI [95%]=[0.183,0.868]	↑
			Tunnel zone 1: OR=0.387, CI [95%]=[0.194,0.771]	↑
			Tunnel length: OR=0.785, CI [95%]=[0.318,1.943]	↑

Table 2: Quantitative results of coded studies for the presence of tunnels and impacts on road safety

2.3 DESCRIPTION OF ANALYSIS CARRIED OUT

2.3.1 Vote-count analysis

After considering the previous points it was decided that a meta-analysis could not be carried out in order to find the overall impact of the presence of tunnels on road safety. Therefore the vote count analysis was completed. In vote count analyses, each study is considered to have one vote for or against the risk factor. The results are summarized in Table 2.

Outcome definition	Tested in number of studies	Result (number of studies)			Result (% of studies)			Result (number of effects)			Result (% of effects)		
		↑	-	↓	↑	-	↓	↑	-	↓	↑	-	↓
Accident frequency	1	1	-	-	100.0%	-	-	1	-	1	50.00%	-	50.00%
Accident numbers	1	1	-	-	100.0%	-	-	2	-	-	100.0%	-	-
Accident or injury severity	3	2	1	-	66.7%	33.3%	-	9	1	2	75.00%	8.33%	16.67%
Behavioural Safety Indicators [Simulation]	1	-	-	1	-	-	100.0%	6	4	8	42.86%	-	57.14%
Total Studies = 6								Total Effects = 34					

Table 2: Vote-count analysis results for tunnel risk factor

2.3.2 Overall estimate for road safety

On a basis of both study and effect numbers, it can be argued that the risk factor of the presence of tunnels, with all its variations, has an overall negative effect on road safety. However there are cases when its impact is inconclusive, or even positive, as has been shown on Table 2. The fact that the majority of studies show a risk effect and that there are a few examples to the contrary leads to the assumption that there is considerable risk, along with some uncertainties. The variation between indicators, models, framing and general details between studies made the circumstances for conducting a meta-analysis inappropriate.

2.4 CONCLUSION

The vote-count analysis carried out showed that tunnels are usually associated with an increased accident frequency (albeit for non-severe accidents). They are usually correlated with an increased risk injury. However, there is one study which shows that tunnel presence induces more careful and conservative behaviour by drivers, reducing their speed and increasing their control of the vehicle, therefore indirectly improving safe road user behaviour. The previous assessment leads to the assignment of the yellow colour code for tunnels.

3 Supporting document

3.1 IDENTIFYING RELEVANT STUDIES

Risk factor: tunnel (or presence of tunnels)

3.1.1 Literature search strategy

The literature search was conducted in Science Direct (Scopus), and the main search terms were variations of *tunnel*, limited to studies published after 1990 in the English or French language. The search focused on hits in the titles, abstracts and key words of journal articles and reports. Titles and abstracts were screened during the search, and studies of potential relevance were screened full-text to assess relevance.

Database: Scopus **Date:** 20th of May 2016

search no.	search terms / operators / combined queries	hits
#1	(„tunnel")	68,621
#2	(„casualties" OR „fatalities" OR „traffic safety" OR „crash" OR „crash risk" OR „severity" OR „frequency" OR „collision" OR „incident" OR „accident")	22,319
#3	#1 AND #2	853

Limitations/ Exclusions:

- published: 1990 to current
- Document Type: "Review" and "Article"
- Language: "English"
- Source Type: „Journal"
- Subject Area: „Engineering")

Results Literature Search

Database	Hits
Scopus (remaining papers after several limitations/exclusions)	853
Total number of studies to screen title/abstract	853

3.2 SCREENING

The abstracts of relevant studies from the initial literature search results were examined to narrow the scope and to detect studies that would be more appropriate at a first stage. Those abstracts give hints as to whether the full text warrants close examination for coding and inclusion in the project.

Total number of studies to screen title/ abstract	853
-De-duplication	0
-Exclusion criteria A (not related to the topic/not relevant risk factor)	826
-Exclusion criteria B (part of meta-analysis)	0
Remaining studies	27
Not clear (full-text is needed)	10
Studies to obtain full-texts	27

3.3 ELIGIBILITY

Total number of studies to screen full-text	34
Full-text could be obtained	27
Reference list examined Y/N	Yes (+7 additional papers)
Preliminary Eligible papers	19 (15 uncertain-full text or further screening is needed)
Final Eligible papers (coded)	6

3.4 PRIORITIZING CODING

During the previous steps 34 studies were detected that could be appropriate for the scope of this synopsis. However, since that number was large, and coding time was finite, there was a final selection process in order to determine the best studies for the analysis. The process was conducted via prioritizing, based on the following criteria:

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals)

Comments: No meta-analysis studies were found.

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3.5.2 List of coded studies

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2. CALVI, A., DE BLASIIS, M. R. & GUATTARI, C. 2012. An empirical study of the effects of road tunnel on driving performance. Procedia-Social and Behavioral Sciences, 53**,** 1098-1108.
3. MA, Z., STEVEN, I., CHIEN, J., DONG, C., HU, D. & XU, T. 2016. Exploring factors affecting injury severity of crashes in freeway tunnels. Tunnelling and Underground Space Technology, 59**,** 100-104.
4. MONTELLA, A. & IMBRIANI, L. L. 2015. Safety performance functions incorporating design consistency variables. Accident Analysis & Prevention, 74**,** 133-144.
5. RAHMAN, M. M., KATAN, L. & TAY, R. Injury risks in collisions involving buses in Alberta. Transportation Research Board Annual Meeting, 90th, 2011, Washington, DC, USA, 2011.
6. XING, Y., LU, J. & WANG, C. 2015. Single Vehicle Traffic Accidents in Shanghai River-crossing Tunnels.

Synopsis 19: Cross-section deficiencies - Superelevation

1 Summary

J.W.H. van Petegem, G. Schermers (SWOV, sept. 2016)

1.1 COLOUR CODE : YELLOW

The coded studies show that an increase in the superelevation relates to a decrease in crashes. Reversely it can be stated that a deficient superelevation relates to an increase in crashes. Although studies used different methodologies and analysed different outcomes, the results were consistent in showing that a superelevation deficiencies (typically defined as difference between the actual and the optimal superelevation) relate to a higher risk on crashes in curves.

Keywords
Superelevation, curves, crashes, road safety, design speed, operating speed

1.2 ABSTRACT

The superelevation is the right-angled slope of the road surface and is part of the horizontal curve design. Driving through a curve at too high speeds can create too high centrifugal forces causing a vehicle to skid (if the skid resistance is also too low) or to roll over. In combination with other curve design components like the curve radius and pavement friction, the superelevation decreases the risk of skidding or rolling over for vehicles driving through the curve at the design speed. Apart from reducing the risk of skidding or rolling over, the superelevation provides for water runoff. The superelevation can also increase crash risk when it is too high. It can cause vehicles too slide or roll over inwards toward the curve. The risk of such an event increases given the combination of too high superelevation rates, vehicles driving slowly, the road is slippery or on combinations of horizontal curves and vertical grades. Four coded studies all found that superelevation deficiencies relate to an increase in crashes at curves. Passenger vehicles were found to be more prone to skidding than rolling over. Heavy good vehicles on the other hand were found to be prone to rolling over due to a relatively high centre of mass. Also, the studies indicated that taking operational speeds into account in the design and evaluation of curves will result in a more robust curve design.

1.3 BACKGROUND

1.3.1 Definitions of the superelevation at curve

The superelevation is the right-angled slope of the road surface (see figure 1) and is part of the horizontal curve design.

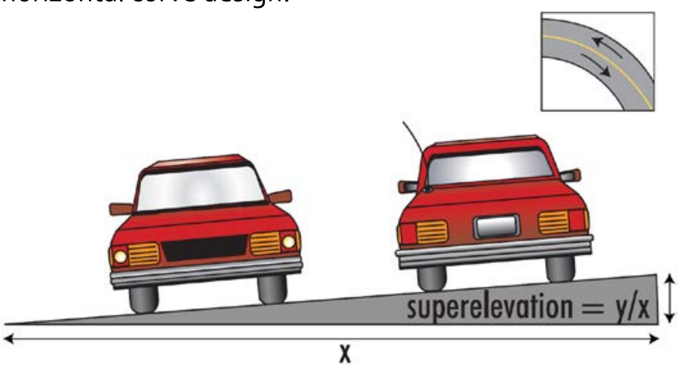


Figure 1 Superelevation

A positive superelevation is directed towards the inside of the curve, while a negative superelevation is directed towards the outside of the curve.

Other known terms for superelevation are cross slope, camber and cross fall. These terms are also associated with tangents or the side slope of the road, whereas the term superelevation is specifically used for the transverse incline of the road at curves.

Other important definitions are:

- Curve radius : The radius R of a horizontal curve (as a measure of the tightness/wideness of the curve)
- Side friction : The right angled friction between the road surface and the vehicle tyres.

1.3.2 How does the superelevation in curves affect road safety?

The superelevation helps to prevent vehicles from skidding or rolling over when driving through a curve, as well as facilitates the drainage of water in the curve. The superelevation rate in combination with the lateral skid resistance compensate the centrifugal forces of a vehicle allowing it to safely negotiate the curve at (or even slightly higher than) the design speed.

Too high a superelevation rate may result in vehicles drifting to the inside of a curve or rolling over to the inside of a curve. This can happen due to a combination of several of the following aspects: combination of vertical grade and horizontal curve, low vehicle speeds, high vehicle mass with a high centre of gravity, inward directed wind gusts ea..

The superelevation is not an isolated component of the road design, but part of the horizontal curve design. The major components in the design of a single curve related to rollover and skidding are the curve radius, vehicle speed, mass, centre of mass and dynamics, friction factor (the right angled friction between the road surface and vehicle tyre) and the superelevation. The effect of the superelevation depends on the composition of these factors.

1.3.3 Which safety outcomes are measured in studies on the superelevation in curves?

The effects of superelevation in terms of safety outcome are measured as the number of crashes, driven speed or as a type of crash risk.

Different crash types are considered as the safety outcomes. Most often all crashes at curves, rollover crashes, head on collisions or single vehicle crashes are analysed. A differentiation between passenger vehicles and heavy good vehicles is sometimes also made, as the risk on skidding or rolling over is different for passenger cars and heavy good vehicles due to the difference in mass and the height of the centre of mass.

Driven speeds are another outcome for the analysis of the safety effect of the superelevation. Speed models incorporate several curve design variables to estimate the driven speeds on curves. Those speed models can also be used to estimate the risk on crashes by skidding or rolling over. This type of analysis investigate the interaction between curve design, driven speeds and risk of crashes.

1.3.4 How is the effect of the superelevation in curves on crashes studied?

Several types of study design are used to analyse the different outcomes related to changes in the superelevation rates. Crash numbers are analysed with regression analysis and through the development of crash prediction models (CPMs). A simple crash percentage comparison has also been found.

Speed models and speed distribution are analysed in various ways. This includes analysing the interaction between the curve design and driven speeds and the effect of this interaction on crash risk. This can be included in CPMs where a superelevation deficiency is determined based on the curve characteristics and speed estimations for those curves. The superelevation deficiency is then used as an independent variable in the CPM. Using Monte Carlo simulation distributions of speed and pavement friction are sometimes incorporated to simulate the crash risk, given design combinations of curve radius and superelevation rate.

1.4 OVERVIEW RESULTS

A total of 23 studies were selected as candidate studies for coding. Six studies were selected for coding. However, for one of these the results were not coded as the methodology was not sound and for another study the results seemed biased and definitions of the superelevation were unclear. Therefore these two studies were not taken into account for the review of studies in the synopsis. The results of the remaining studies are consistent in the direction of the effect of the superelevation, namely that increases in superelevation rate relate to decreases in the number of crashes.

2 Scientific overview

2.1 LITERATURE REVIEW

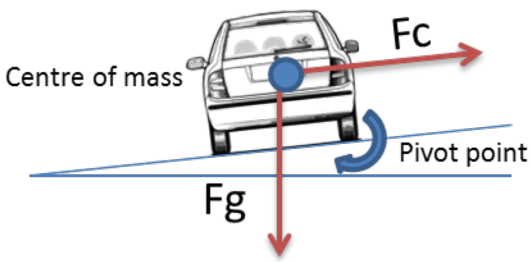
The literature review is based on the studies selected for coding. It comprises an overview of the findings on the effects of superelevation in horizontal curves on road safety.

2.1.1 Definition of the superelevation and the effect on road safety

The superelevation is the right angled slope of the road surface and is part of the horizontal curve design (see Figure 1). Figures 2 and 3 display the main forces on the vehicle in the mechanism of skidding and rolling over.

Figure 2 Forces related to the mechanism of skidding

Figure 3 Forces related to the mechanism of rolling over



Driving through a curve results in a centrifugal force (Fc) directed to the outside of the curve. If this force is too great and not balanced by other forces on the vehicle, it can result in a lateral skid or the vehicle rolling over in the direction of the centrifugal force. The centrifugal force is determined by the vehicle speed, the mass of the vehicle and the curve radius. The higher the vehicle speed, the higher the vehicle mass or the smaller the curve radius, the higher centrifugal force (keeping the other components constant) and thereby increasing the risk on a skidding or rollover incident.

The risk of skidding due to the centrifugal force is counteracted by the side friction force (Fsf) and a gravitational force (Fg) directed to the inside of the curve as a result of the superelevation. The difference between the centrifugal force and the gravitational force due to the superelevation is called the side friction demand. The side friction force is bound by a maximum as a result of the friction of the road surface, vehicle tyres and weather conditions. This maximum is called the maximum side friction supply. When the side friction demand exceeds the side friction supply, the vehicle will skid.

The risk on rolling over due to the centrifugal force is counteracted by a gravitational force on the vehicle, and the position of the centre of mass. The centrifugal force creates a momentum, shifting the weight to the outer wheels of the vehicle (pivot point in figure 3). The higher the centre of mass, the greater the distance of the centrifugal force to the pivot point thus the greater the outward momentum due to the centrifugal force. The gravity on the centre of mass counteracts the momentum due to the centrifugal force. The superelevation increases the distance from the vector of the gravitational force to the pivot point, increasing the inward momentum.

2.1.2 Description of coded studies

Four coded papers were included in the analysis of the risk factor for the superelevation in curves, reflecting different risks and approaches to the relationship between the superelevation in curves and road safety (as expressed in terms of crashes and speed relationships). Two studies reported a cross sectional analysis of the relationship between crash rates and a superelevation deficiency for two way two lane rural roads (Voigt, 1996; Zegeer et al., 1990). In both studies the superelevation deficiency was defined as the difference between the optimal superelevation and the actual superelevation. Zegeer et al. defined the optimal superelevation as the superelevation rate recommended by the AASHTO design guidelines which makes use of a fixed design speed. However, Voigt analysed different optimal superelevation definitions, including estimations of operating speeds instead of fixed design speeds.

Zegeer et al. analysed the relationship between curve components and crashes aimed at identifying cost-effective curve improvements. The primary database for the analysis contained over 10000 curves. However, information on the superelevation could only be collected on a small subset of 732 curves and used in the analysis on superelevation. The relationship between crashes and superelevation rate was analysed with the help of regression analysis. The dependent variable of the model was the crash rate which was presumably assumed as normally distributed. Covariates were the degree of curvature, road width, spiral presence and superelevation deficiency.

By determining expected values for degree of curve, road width and spiral presence and varying the superelevation deficiency Zegeer et al. concluded that an increase of the superelevation deficiency of 0.02 would relate to an increase of the crash rate of 10 percent.

Voigt (1996) analysed the effect of different approaches for curve design on the relationship with crashes. A standard approach for curve design is designing curves based on a design speed choice. This can be the speed limit or a higher speed, which would better reflect operating speeds, depending on the circumstances. Voigt suggested the use of (estimated) operating speeds in curve design, as he found enough evidence that standard design speeds do not necessarily reflect operational speeds. Literature findings suggested that the 85^{th} percentile operating speeds of many curves exceeded design speeds on curves with design speeds less than 90-100 km/h. To check if operating speeds are expected to be above or below the safe design speed, speed estimation models can be used. Voigt tested several linear speed models to estimate the V85 operating speed. Superelevation proved to be a statistically significant component in these models. To analyse the difference between curve design approaches using design speeds or operating speeds, Voigt also developed several linear regression models with the log of the crash rate as the dependent variable, and the superelevation deficiency as the independent variable (with only an intercept as covariate)[1]. In these models the superelevation deficiency was the difference between the actual and the optimal superelevation, in which for each design approach the optimal superelevation was determined. The results showed that models based on a design approach using estimated operating speeds fitted far better than the 2 models based on a design speed approach. This suggests that the design speed approach does not always reflect operational speeds. In cases where operating speeds are higher than design speeds, the use of only design speeds in the curve design process would thus result in deficient curves. Therefor iterations are needed in the design process to check if operation speed is expected exceed safe design speeds or not.

Another approach adopted in one of the coded studies was the reliability analysis of the curve design (You & Sun, 2013). This study used a driver/vehicle/road dynamic simulation model to determine if a combination of circumstance would result in a rollover or skidding incident. A Monte

[1] The only covariate was the intercept, as other curve components like curve radius and operating speed are already reflected in the determination of the superelevation deficiency

Carlo simulation was used to determine the probability of failure for different scenario's in which failure was defined as a situation resulting in skidding or rolling over as calculated by the driver/vehicle/road dynamic simulation model. Within the scenarios the speed and side friction factor were assumed as normally distributed stochastic variables and the curve radius, superelevation and grade as deterministic variables. Several combinations of grades and superelevation were tested with a fixed value for the curve radius of 160 meters. The means and variance for the speed and side friction factor were determined based on a literature review. The simulation showed that for different combinations of grade and superelevation the probability of failure for skidding for a passenger car (SUV) was consistently higher than the probability of failure for rolling over. This would however not be the case for heavy good vehicles due to the relative high centre of mass, which make those vehicles more prone to rolling over. An increase in the superelevation also showed a decrease in the probability of failure for both rolling over and skidding. Finally an increase in the grade (uphill) resulted in an increase in the probability of rolling over or skidding. This last result might be counter intuitive, but the model assumes a constant speed through the curve, despite the grade. That means that the grade does not result in lower speeds in the model, and thus the centrifugal force will not decrease as a result from the grade. The increase in the probability of failure due to the grade will therefore be due to vehicle dynamics.

Milliken and De Pond investigated the risk on rollover crashes by examining vehicle dynamic characteristics of heavy good vehicles (HGV) and road characteristics (Milliken & De Pont, 2004). They used an analysis of Mueller et al.(Mueller, De Pont, & Baas, 1999) to estimate the effect of the superelevation on rollover crashes. Mueller et al. analysed the relation between rollover crashes and the static rollover threshold (SRT), which is the lateral acceleration require to cause a rollover incident. Rollover crashes were identified from a crash dataset from New Zealand for which also the SRT of the HGVs could be determined. The relative crash rate was defined as the number of crashes of HGV of a certain SRT class, divided by the fleet population of that SRT class. Mueller et al then fitted a heuristic function for the crash rate as a function of the STR. Milliken et al. used this function to estimate the effect of the superelevation on crash rates. To this end, they assumed that the effective SRT (SRT effective) is equal to the SRT + the superelevation. Based on this assumption and the heuristic function as determined by Mueller et al., Milleken et al. estimated that an increase of the superelevation of 0.01 relates to a 5% reduction in rollover crashes of HGV.

Both Milliken and De Pond and You and Sun indicate that rollover crashes are a typical problem for HGV.

2.2 ANALYSIS METHODS AND RESULTS

2.2.1 Introduction

The estimates in the coded studies were subject to different statistical methods and different outcomes. These differences do not allow for a meta-analysis. The effects however all point in the same direction, namely that increases in the superelevation rate leads to a reduction in the crash rates, specifically crashes related to run-off road/skidding and roll overs.   The main effects can be summarised as follows.

- With superelevation deficiency defined as the difference between the optimum superelevation and the current superelevation , an increase in the superelevation deficiency is found to relate to an increase in crash rates at curves.(Voigt, 1996)
- An increase in the superelevation consistently relates to lower risks for skidding or rollover crashes

- For passenger cars , the risk of skidding is consistently higher than the risk on rolling over for different combinations of superelevation and grades (for a constant curve radius and side friction coefficient) (You & Sun, 2013)
- An increase of the superelevation rate by 0.01 relates to a decrease of the rollover crash rate of heavy good vehicles by 5% (Milliken & De Pont, 2004)
- Other research found a crash reduction as much as 10 percent for curves with an optimal superelevation (Zegeer et al., 1991)

Related to speed estimation at curved road segments, the findings can be summarised as follows:

- The superelevation rate has a significant effect on the estimation of driven speeds on a curve (V85) (Voigt, 1996). An increase in the superelevation relates to an increase in the V85.Similarly, an increase in the curve radius relates to an increase in the V85.
- Including speed distributions or speed estimation into the analyses of the risk on skidding or rollover crashes would improve the reliability of the analysis, as there is a complex interaction between the curve design and driven speeds
    - Larger curve radii and a higher superelevation relates to higher speeds
    - Higher speeds and smaller curve radii increase the centrifugal force thus increase the side friction demand and rollover momentum
    - Higher superelevation rates decrease the side friction demand and rollover momentum

Table 1 presents on overview of the main features of the coded studies

Author, Year	Sample and study design	Method of analysis	Outcome indicator	Main results
Zegeer C. V. et al., 1991	The analysis on superelevation was done on a set of 732 curves on two lane rural roads in Washington State. A cross sectional study design was employed to analyse the relation between crashes and superelevation. The models developed corrected for the degree of curves, road width and presence of spirals. The analysis was part of a larger study on horizontal curve features that affect accident experience on two-lane rural roads.	Models were developed by different regression analysis. Linear models were developed with the accident rate as the dependent, probably with an assumed normal distribution function. Non- linear models were developed with the log of the number of accidents as the dependent. This regression analysis methodology is however not fully specified. The probability distribution function is not known.	Different outcome indicators were used. The outcome indicator for the final reported result was the accident rate.	The main result of the study with regards to the superelevation was an increase of the accident rate by 10 percent for a superelevation deficiency of 0.02. However, superelevation correlated with road width, also present in the model. Furthermore, spirals correlated with road width, also present in the model.
Voigt A. , 1996	The study analysed the relation between curve design and driver speed and between curve design and crash risk. 2 separate research databases were used for the 2 analysis. A speed-geometry database was used including 138 curves and 78 approach tangents. A curve-geometry database was used including 247 curves, including crash data from the period 1987-1993 counting 238 curve related crashes. The study design was cross sectional.	Models were developed with linear regression analysis. The depend for the speed model was V85 (85^{th} percentile speed at the midpoint of the curve), which was assumed to be normally distributed. The dependent for the crash analysis was the log of the crash rate + 0.1, which was assumed to be normally distributed.	Two outcome variables were studied: V85 and accident rate + 0.1. Both were assumed to be normally distributed.	The main results of the study were the identified relation between superelevation and V85 and between superelevation and crash rate. An increase in the superelevation was found to relate to an increase in the V85 but a decrease in the crash rate. The relation between crash rates and superelevation deficiency based on estimated driven speeds showed to be a lot stronger than with the superelevation deficiency based on standard design speeds. Suggesting that design speeds do not represent actual driver behaviour and curve design might be flawed when these design speeds are used.

Milliken and De Pont, 2004	(In-depth) Crash analysis of rollover crashes of heavy good vehicles in New Zealand. The number of crashes is unclear	A non-parametric regression analysis on the relative crash rate as the dependent and	Relative crash rate of the number of heavy good vehicle rollover crashes as a function of the rollover crash rate, relative to the rollover crash rate for the total population of trucks	It was found that an increase of 0.01 of the superelevation might reduce rollover crashes of heavy good vehicles by 5%.
You K. and Sun L., 2013	Reliability analysis of the curve design by use of a driver/vehicle/curve dynamic simulation model.	A driver/vehicle/curve dynamic simulation model in combination with a monte carlo simulations is used to determine the probability of failure, meaning a rollover or skidding incident.	Probability of failure, with failure defined as a rollover or skidding incident.	For passenger cars, for different combinations of grade and superelevation, the probability of skidding is consistently higher than the probability of rolling over.

2.2.2 Overall estimate for accident severity

Although approaches of the coded studies varied, the overall conclusion can be that an inappropriate superelevation may increase several crash outcomes; accordingly, an increase in the superelevation when applied appropriately reduces the risk of rollover and skidding crashes. The studies of You and Sun (2013) and Voigt (1996) also suggest that the curve design will be more robust by incorporating operating speeds instead of fixed design speeds which may result in deficient curve designs.

As the studies are too diverse and numbers per type of study are too small, a meta-analysis to determine a common quantified risk factor was not possible.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature search aimed at identifying the highest quality and most recent studies aimed at quantifying the relationship between superelevation in curves and cross slope and crash occurrence (number of crashes) and crash severity. The document search strategy aimed at sourcing the most recent studies undertaken in Europe and published in recognised scientific journals and publications. Failing that, the search fell back on older studies and/or studies from other parts of the world but with the proviso that these were published in recognised scientific publications. The Scopus and TRID databases were searched and abstracts were scanned to make a first selection of relevant literature. All searches were filtered on English results only.

To select papers relating to road safety in Scopus, the following query is used: ((road and casualt*) or (road and injur*) or (road and accident*) or (road and crash*) or (traffic and injur*) or (traffic and casualt*) or (traffic and accident*) or (traffic and crash*)).

To select papers relating to road safety in TRID, the following query is used: (collision* or crash* or accident* or injur* or casualt*) AND (traffic or road).[2]

The aforementioned queries were combined with two queries to select papers relating to the risk factors super elevation at curves and cross slope: ((roadway or road or carriageway) and (camber or crossfall or "cross-slope" or "cross slope")) ((curve or bend) and ("bend banking" or superelevation))

These queries were combined in Scopus and TRID to search for literature about the risk factor superelevation at curves. To distinguish literature from Europe and the rest of the world the results were loaded into Mendeley, where the following query was used to identify literature from Europe: (Italy or Ireland or Hungary or Greece or Germany or France or Finland or Estonia or Denmark or Czech or Cyprus or Croatia or Bulgaria or Belgium or Austria or Scotland or England or Britain or United Kingdom or Sweden or Spain or Slovenia or Slovakia or Romania or Portugal or Poland or Netherlands or Malta or Luxembourg or Lithuania or Latvia).

The number of hits for Europe and worldwide and for Scopus and TRID are presented in Table 1.

Table 1 Literature search strategy

search no.	Risk Factor	Region	Database	hits
#1	Superelevation at curves	Europe	Scopus	2
#2	Superelevation at curves	Europe	TRID	3
#3	Superelevation at curves	Worldwide	Scopus	22
#4	Superelevation at curves	Worldwide	TRID	68

[2] The difference in the queries is due to differences in restrictions to the query length between the two sources.

#5	Cross slope	Europe	Scopus	3
#6	Cross slope	Europe	TRID	38
#7	Cross slope	Worldwide	Scopus	31
#8	Cross slope	Worldwide	TRID	206

Following the initial selection of relevant publications, a new selection of publications was made in Mendeley, sorting the publications by year and source. Only publications from trusted sources and most recent publications were selected with a maximum number of about 80 for both superelevation and cross slope. From this selection all abstracts were reviewed. From reviewing the abstracts a a selection of the most promising papers for coding was selected. From reviewing the full texts, it occurred that all papers thought to be related to cross slope were related to superelevation. From 23 studies, 6 studies have been coded.

3.2 LIST OF STUDIES

The following 6 studies have been coded:

Milliken, P. and J. De Pont. 2004. "The Effect of Cross-Sectional Geometry on Heavy Vehicle Performance and Safety." *TRANSFUND NEW ZEALAND RESEARCH REPORT* (263):46P. Retrieved (https://trid.trb.org/view/781897).

Othman, Sarbaz and Robert Thomson. 2007. "Influence of Road Characteristics on Traffic Safety." P. 10p in. Retrieved (http://www-nrd.nhtsa.dot.gov/departments/esv/20th/).

Voigt, A. P. and R. Krammes A. 1998. "AN OPERATIONAL AND SAFETY EVALUATION OF ALTERNATIVE HORIZONTAL CURVE DESIGN APPROACHES ON RURAL TWO-LANE HIGHWAYS." Pp. p. 11:1–8 in *Transportation Research Circular*. Transportation Research Board. Retrieved (http://onlinepubs.trb.org/onlinepubs/circulars/ec003/toc.pdf).

You, Kesi and Lu Sun. 2013. "Reliability Analysis of Vehicle Stability on Combined Horizontal and Vertical Alignments: Driving Safety Perspective." *Journal of Transportation Engineering* 139(8):804–13. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84881224709&partnerID=tZOtx3y1).

Zegeer V, Charles, J. Stewart Richard, Forrest Council M, Donald Reinfurt W, and Elizabeth Hamilton. 1992. "SAFETY EFFECTS OF GEOMETRIC IMPROVEMENTS ON HORIZONTAL CURVES." *Transportation Research Record* (1356):p. 11–19. Retrieved (http://scholar.google.com/scholar_lookup?title=SAFETY+EFFECTS+OF+GEOMETRIC+IMPROVEMENTS+ON+HORIZONTAL+CURVES&author=C.+Zegeer&author=J.+Stewart&author=F.+Council&author=D.+Reinfurt&author=E.+Hamilton&publication_year=1992).

Zegeer, C. et al. 1991. *Cost-Effective Geometric Improvements for Safety Upgrading of Horizontal Curves*. Retrieved (https://trid.trb.org/view/1172224).

The following studies have been considered for coding:

Brewer A, Marcus, Akram Abu-Odeh, Kimberly Rau, Darren Torbic, and Elizabeth Depwe. 2016. "Effects of Cross-Slope Break on Roadway Departure Recovery for Trucks on Horizontal Curves." *Transportation Research Record: Journal of the Transportation Research Board* (2588):pp 12–21. Retrieved (http://dx.doi.org/10.3141/2588-02).

Cerezo, Veronique, Minh-Tan Do, and Eric Violette. 2011. "A Global Approach to Warn the Drivers Before a Curve by Considering the Decrease of Skid Resistance Due to the Rain." P. 21p in. Retrieved (http://onlinepubs.trb.org/onlinepubs/conferences/2011/RSS/3/Cerezo,V.pdf).

Chen, S. R., C. S. Cai, and B. Wolshon. 2009. "From Normal Operation to Evacuation: Single-Vehicle Safety under Adverse Weather, Topographic, and Operational Conditions." *Natural Hazards Review* 10(2):68–76. Retrieved April 5, 2016 (http://ascelibrary.org/doi/abs/10.1061/(ASCE)1527-6988(2009)10:2(68)).

de León Izeppi, Edgar, Samer Katicha, Gerardo Flintsch W, and Kevin McGhee K. 2016. "Pioneering the Use of Continuous Pavement Friction Measurements to Develop New Safety Performance Functions, Improve the Accuracy of Crash Count Predictions, and Evaluate Possible Treatments for the Roads in Virginia." P. 16p in. Retrieved (http://docs.trb.org/prp/16-4952.pdf).

Donnell, Eric, Jonathan Wood, Scott Himes, and Darren Torbic. 2016. "Use of Side Friction in Horizontal Curve Design: A Margin of Safety Assessment." P. 21p in. Retrieved (https://trid.trb.org/view/1393917).

Fitzpatrick, Kay. 1994. "Horizontal Curve Design: An Exercise in Comfort and Appearance." *Transportation Research Record* (1445):47–53. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-0028745565&partnerID=tZOtx3y1).

Fitzpatrick, Kay, Karl Zimmerman H, Roger Bligh P, Susan Chrysler, and Byron Blaschke. 2007. *Criteria for High Design Speed Facilities*. Retrieved (http://tti.tamu.edu/documents/0-5544-1.pdf).

Hanley, K. E., A. R. Gibby, and T. C. Ferrara. 2000. "ANALYSIS OF ACCIDENT-REDUCTION FACTORS ON CALIFORNIA STATE HIGHWAYS." *Transportation Research Record* (1717):p. 37–45. Retrieved (http://dx.doi.org/10.3141/1717-06).

Lin, Feng-Bor. 1990. "Flattening of Horizontal Curves on Rural Two-Lane Highways." *Journal of Transportation Engineering* 116(2):181–86. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-0025400749&partnerID=tZOtx3y1).

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Synopsis 20: Cross-section deficiencies - Number of lanes

1 Summary

B. Loenis, G. Schermers, J.W.H. van Petegem (SWOV, sept 2016)

1.1 COLOUR CODE: RED

Research shows that the variable number of lanes can contribute to the number of crashes. Regardless of the included covariates and used methods the effect of an increasing number of lanes is in the vast majority of cases negative (an exception for mountainous roads was detected). The effect of number of lanes on crashes depends upon its interaction with other characteristics of the roadway, specifically, lane width and shoulder width.

1.2 KEYWORDS

Crashes, number of lanes

1.3 ABSTRACT

Most of the studies show that an increasing number of lanes is related to an increase in crashes. This might be partly contributed to an increase in lane changing and overtaking manouevres and speed differences between vehicles. Another relationship is that a higher number of traffic lanes relates to a higher traffic demand. This means that the relation between number of lanes and crashes is not causal. The effect of the number of lanes on crashes always concerns the number of crashes or total crash reduction, for which often a distinction has been made in crash severities. A distinction between crash types is rarely found. One study indicates a decreasing number of crashes for an increase of lanes, while the remaining studies indicate the opposite. The difference is caused by the interaction with other variables like annual average daily traffic (AADT), speed limits, lane width, road type and the percentage of heavy good vehicles (HGV). Most of the studies involve Crash Prediction Models (CPMs).

1.4 BACKGROUND

1.4.1 How does the number of lanes affect road safety?

The general consensus on the risk factor number of lanes is that an increasing number of lanes is associated to more crashes. One of the hypotheses is that an increase the number of lanes implies an increases the interaction between drivers, due to an increase in overtaking manouvres and lane changing manouvres. Moreover, drivers may have more opportunities to maneuver around slower traffic as the number of lanes increases. This may create high speed differential between lanes, resulting in more side-swipe and rear-end crashes. The number of potential lane-change related conflicts on a road with two lanes is 2. This number will increase up to 7 and 16 for roads with three and four lanes (Kononov et al. 2008).

However, the increase in the number of lanes cannot be disassociated from increases in traffic volume. The number of lanes is determined by the traffic demand. Thus a higher number of lanes is related to a higher traffic demand. And as a higher traffic demand relates to more crashes, a higher number of lanes will also relate to more crashes. One of the studies included mountainous roads which are exposed to adverse weather and showed that more lanes lead to less crashes. The increase of safety due to the increase in number of lanes is plausible since the specific freeway has a high percentage of trucks which could be confined to the two right lanes providing more space for other vehicles and contributing to easier maneuvers and less speed variance.

The outcome of the study depends on the road and traffic characteristics of the analyzed road(s) which may be different for each study.

1.4.2 Which safety outcomes are affected by the number of lanes?

The effect of the number of lanes on road safety has frequently been studied in terms of crash frequency (number of crashes). In most studies a distinction has been made in terms of crash severities, namely total, fatal, serious injuries and accidents. Studies seldom mention crash types and/or the types of traffic involved. Generally, it is clear that it concerns motorized vehicles and not pedestrians, cyclists or other slower traffic modes.

1.4.3 How is the effect of number of lanes on crashes studied?

The majority of international literature estimates the effect of the number of lanes on crashes by developing Crash Prediction Models (CPMs) through the application of generalized non-linear regression models. The majority of studies identified the relationship between the number of crashes (dependent variable) and any number of road design and other features (the independent or predictor variables) and often takes the form of a Negative Binomial, Poisson or Full Bayesian model.

This synopsis focusses on studies conducted between 2011 and 2014 from the USA (2x), Spain, UK and New Zealand.

1.5 OVERVIEW RESULTS

A total of 22 studies were selected as candidate studies for coding. Of these only 5 were found to be suitable and provided sufficient methodological detail allowing the effects to be coded. The results of the selected studies are similar although the direction of the effect is varied with three studies showing increases in crashes and two decreases. The reasons for these differences lie in the differences in the methodological approaches followed and the fact that the multiple regression models comprise different sets of dependent and independent variables. Furthermore, the effects were calculated for different (sub) sets of crash data including differences in environmental surroundings (rural, urban), traffic composition (proportion of HGV), geometrical aspects (curvature, slopes and lane width) and legislation (speed limits). Meta-analysis of these results was therefore not sensible nor advised (Elvik et al, 2009[1]).

Potential transferability of results is questionable, due to the fact that this risk factor has not been investigated under a wide range of conditions. The main restriction is that the vast majority of studies concern regional locations. It is therefore not feasible to produce an overall estimate for the effect of the number of lanes on the number of accidents.

Four of the five studies show a negative effect on road safety for an increasing number of lanes. The last study shows a positive effect on road safety for an increasing number of lanes. Overall the studies which investigate the single effect of the number of lanes are in line. The four studies showing a negative effect are methodologically similar (although using different datasets and conditions). The positive study takes mountainous roads with adverse weather conditions into account. Overall the basic studies reveal negative effects on road safety for an increasing number of lanes and this may vary for more complicated models with extended data.

1.6 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound. Most of the studies are based on statistical regression models using different sets of dependent and independent variables. The studies mainly focus on regional networks with specific characteristics and limited available data which make it difficult to estimate the reliability of the results and the

[1] (Elvik, Hoye, Vaa, & Sorensen, 2009)

possibility for comparison. Moreover, the effect has not been tested under the same or under all conditions and more studies are needed. Overall, the topic has not been deeply studied. Because of the fact that the study designs, the applied methods and input data are somewhat heterogeneous and inconsistent, potential transferability of results is unlikely.

2 Scientific overview

2.1 DESCRIPTION OF AVAILABLE STUDIES

2.1.1 Definition of number of lanes

The risk factor number of lanes is defined as the number of driving lanes of multilane urban and rural highways. In some studies the number represents the number of lanes for a single direction, in other studies it represents the number of lanes of both directions combined. In almost all studies the number of lanes is included as a dummy (or dichotome) variable. A dummy variable takes the value of 0 or 1, indicating whether the variable number of lanes is either present or absent. In all studies the reference situation represents road segments with the lowest number of lanes and is compared to road segments with additional lanes. In four of the five studies the number of lanes per direction in the reference situation is equal to two lanes. The fifth study concerns a single lane per direction as reference.

2.1.2 What is the relationship between crashes and the number of lanes

5 studies (out of a potential 22) were selected for coding on the basis of being the most recent, relevant (in terms of reported effects of the number of lanes on road traffic crashes) and published in recognized scientific journals. All of these studies were coded.

All five studies investigated the relationship between crash frequency (number of accidents) and the number of lanes. Three of these studies specified the crash frequencies according to crash severity (total, fatal, serious injury and accidents). One of the studies specified the crash frequency according to crash location (urban, rural, with on-ramp, with off-ramp and without ramps). One study didn't make any specifications in terms of crash severity or crash type. The five investigated studies report the effects based on the development of a Crash Prediction Model (CPM) or a Safety Performance Function (SPF).

A paper by Ahmed et. al (2011) presents an exploratory investigation of the safety problems of a mountainous freeway section of unique weather conditions and geometric variables, including the number of lanes, curve radius, deflection angle, degree of curvature, median width, shoulder width and curve length. Three models are created including a Poisson model and a Bayesian hierarchical model with spatial and random effects. The variable number of lanes is included as a dummy variable in which 'zero' represents the scenario with 2 driving lanes and 'one' represents the scenario with 3 driving lanes. Based on the statistical test it can be said that the Bayesian models, outperform the Poisson model. All three models give significant outcomes of which the random effect model gives the best model fit. The result was a decrease in the number of crashes of 40% for roads with three driving lanes compared to roads with two driving lanes, with all other factors being equal.

A paper by Rangel et. al (2013) presents a negative binomial regression model to determine the relationship between crashes and highway characteristics like AADT, average speed, percentage of HGV, number of lanes and number of intersections. Three models have been developed in order to estimate the effect for different crash severities including accidents, injuries and fatalities. Although it is known that the number of lanes varies between 4 and 8 lanes (with an average of 4,2), the paper does not report the conditions very clearly. For all three models the coefficient is positive, implying an increase in the number of crashes for an increasing number of lanes. The exact numbers used for comparison are not mentioned in the paper, only the coefficient and the final conclusion.

A paper by Islam et. al (2014) developed crash prediction models for freeways using negative binomial distributions and by considering interactions between speed limit and selected geometric variables. Models were estimated for four crash categories: single vehicle total crashes, single vehicle fatal and injury crashes, multi vehicle total crashes, and multi vehicle fatal and injury crashes. The study compares road segments with 4 driving lanes (reference condition) to road segments with 6 and 8 driving lanes. No significant relationships were found for single vehicle crashes, only for multi vehicle crashes between 4 and 8-lane roads. These results are in line with the theory that more lanes lead to more interaction between drivers and can therefore lead to more crashes between vehicles. More lanes do not imply an increase in single vehicle crashes. Since the relationship between multivehicle crashes on 4- and 6-lane road sections were statistically similar, these road segments were combined to represent a new reference condition. Analysis revealed that the only significant results were found for fatal and injury crashes involving multiple vehicles. For the variable 8 lanes a significant positive coefficient was found for fatal and injury crashes, implying an increase in the number of crashes for an increased number of lanes.

A paper by Quddus (2013) explored a series of relationships between average speeds, speed variation, road geometry and crash rates based on the major road network around London. Two models were used in this study, a non-spatial random-effects negative binomial model and a spatial Poisson-lognormal model using a full hierarchical Bayesian model to explore the relationship. Both models predict crash rates for killed and severely injury (KSI) and slightly injured (SI) crashes. In both models 2 lane road segments (reference) are compared with 3 and 4 lane segments. For both models significant positive coefficients were found, implying an increase in the crash rate with an increase in the number of lanes. Both models show a higher coefficient for SI crashes compared to KSI crashes, a lower coefficient for 4 lanes KSI crashes compared to 3 lanes KSI crashes and a higher coefficient for 4 lanes SI crashes compared to 3 lanes SI crashes.

A study by Chengye et. al (2013) presents a crash prediction model using negative binomial regression. Prediction models were developed for three different categories: the whole motorway; rural and urban motorway segments separately; and motorway segments with an off-ramp, on-ramp and without ramps separately. The variable number of lanes varies between 2 and 5 lanes, with an average of 2,76. In the study there is no distinction between 2 and 4 lanes or 3 and 4 lanes, only the general effect of increasing the number of lanes is given. For all categories the coefficients are positive, implying an increase in the number of crashes with increasing number of lanes. The coefficient of rural segments is higher than the coefficient of urban segments, implying a higher increase of crashes on rural segments. For road segments with either an off-ramp or an on-ramp the coefficient is almost equal. The coefficient for road segments without a ramp is slightly higher, implying a higher increase of crashes.

2.2 ANALYSIS METHODS AND RESULTS

2.2.1 Introduction

The effects of the number of lanes can be summarized as follows:

- 1 study with an significant decrease of crash frequency for a higher number of lanes (+)
- 4 studies with a significant increase of crash frequency for a higher number of lanes (-)

Table 1 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 1 Description of coded studies

Author(s), Year	Sample and study design	Method of analysis	Outcome indicator	Main result
Ahmed et al (2011)	1877 crashes from 2000 to 2005 collected on 168 road segments. Data includes AADT and roadway characteristics. Full Bayesian study incorporating regression modelling	Poisson model, spatial and random effect Full Bayesian model	Number of crashes	A higher number of lanes leads to significant decrease of crashes
Rangel et al (2013)	5525 crashes from 2007 to 2009 collected on 696 road segments, including 1937 accidents, 3480 injuries and 108 fatalities. Data includes AADT and roadway characteristics. Cross-sectional and observational study incorporating regression modelling	Negative Binomial model	Number of crashes per crash severity (accidents, injuries and fatalities)	A higher number of lanes leads to significant increase of crashes
Islam et. al (2014)	751 crashes from 2009 to 2011 collected on 949 road segments, including 237 single vehicle crashes and 514 multi vehicle crashes. Data includes AADT and roadway characteristics. Cross-sectional study incorporating regression modelling	CPM using a negative binomial distribution	Number of crashes per crash severity (fatal and injurious crashes)	A higher number of lanes leads to significant increase of crashes.
Quddus (2013)	3779 crashes from 2003 to 2007 collected on 298 road segments. Data includes AADT and roadway characteristics. Cross-sectional study incorporating regression modelling	Non-spatial random-effect Negative binomial model and a spatial Poisson lognormal model using a full hierarchical Bayesian model for exploring	Number of crashes per crash severity (killed and severe injuries, slight injuries)	A higher number of lanes leads to significant increase of crashes for all crash severities
Chengye et al (2013)	483 crashes from 2004 to 2010 collected on 137 road segments. Data includes AADT and roadway characteristics. Cross-sectional study incorporating regression modelling	Negative Binomial models	Number of crashes per category (whole motorway, urban and rural segments, with off-ramp or on-ramp and without ramps)	A higher number of lanes leads to significant increase of crashes for all categories

Of the five studies, four indicate that increasing the number of lanes leads to an increased number of crashes. Differences can be noted when additional data or interaction variables are taken into account. Additionally, the effects are based on multiple regressions using different sets of variables and different models whereby the results do not lend them for meta-analysis.

2.2.2 Overall estimate for accident severity

Not all of the coded studies correct for exposure and the estimates are subject to different models with different sets of dependent and independent variables and therefore the estimates are not directly comparable. Estimates solely based on the risk factor number of lanes give mixed results and depend on the independent variables which are used. For example, grade, speed limits, road type, percentage of HGV, curvature etc.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature search aimed at identifying the highest quality and most recent studies aimed at quantifying the relationship between junction density and crash occurrence (number of crashes) and crash severity. The document search strategy aimed at sourcing the most recent studies undertaken in Europe and published in recognized scientific journals and publications. Failing that, the search fell back on older studies and/or studies from other parts of the world but with the proviso that these were published in recognized scientific publications. The Scopus and TRID databases were searched and abstracts were scanned to make a first selection of relevant literature. All searches were filtered on English results only.

To select papers relating to road safety in Scopus, the following query is used: ((road and casualt*) or (road and injur*) or (road and accident*) or (road and crash*) or (traffic and injur*) or (traffic and casualt*) or (traffic and accident*) or (traffic and crash*)).

To select papers relating to road safety in TRID, the following query is used: (collision* or crash* or accident* or injur* or casualt*) AND (traffic or road).[2]

The aforementioned queries were combined with a query to select papers relating to the risk factor absence of shoulder: "narrow lane" or "narrow lanes" or "lane width" or "width of the lane" or "lane widths" or "width of the lanes" or "widths of the lanes").

These queries were combined in Scopus and TRID to search for literature about the risk factor narrow lane. To distinguish literature from Europe and Worldwide, the results were loaded into Mendeley, where the following query was used to identify literature from Europe: (Italy or Ireland or Hungary or Greece or Germany or France or Finland or Estonia or Denmark or Czech or Cyprus or Croatia or Bulgaria or Belgium or Austria or Scotland or England or Britain or United Kingdom or Sweden or Spain or Slovenia or Slovakia or Romania or Portugal or Poland or Netherlands or Malta or Luxembourg or Lithuania or Latvia).

The number of hits for Europe and Worldwide and for Scopus and TRID are presented in table 1.

Table 1 Literature search strategy

search no.	Region	Database	hits
#1	Europe	Scopus	36
#2	Europe	TRID	50
#3	Worldwide	Scopus	124
#4	Worldwide	TRID	372

[2] The difference in the queries is due to differences in restrictions to the query length between the two sources.

Following the initial selection of relevant publications, a new selection of publications was made in Mendeley, sorting the publications on year and source. Only publications from trusted sources and most recent publications were selected with a maximum number of about 80. From this selection all abstracts were reviewed. From reviewing the abstracts a total of 11 publications were selected as the most promising. For 3 of these the full text version could not be retrieved and these were not considered further. The remaining 8 publications were reviewed and 1 of these was adjudged unsuitable for coding (specific effect not reported, topic not specifically addressed etc.).

The final studies selected for the topic narrow lanes suggest that although this topic has been studied in some depth, the study methodologies and subsequent results are diverse and mixed. No meta-analyses were found on this topic and the literature review reveal that the results of the selected five studies do not lend themselves for inclusion in a meta-analysis. The majority of these studies are based on multiple regression models using different dependent and independent variables and with widely varying outcomes.

3.2 LIST OF STUDIES

A detailed list of studies considered (and of which the first 5 were selected for coding) are listed below:

3.2.1 Coded references

1. Costa, J. O. D., M. A. P. Jacques, P. A. A. Pereira, E. F. Freitas, and F. E. C. Soares. 2015. "Portuguese Two-Lane Highways: Modelling Crash Frequencies for Different Temporal and Spatial Aggregation of Crash Data." *Transport*. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-84939474048&partnerID=40&md5=c92a92195e841f33b9097713e98c949d).

2. Dell'Acqua, Gianluca and Francesca Russo. 2010. "Accident Prediction Models for Road Networks." P. 11p in. Retrieved (https://trid.trb.org/view/1100358).

3. Manuel, Aaron, Karim El-Basyouny, and Md. Tazul Islam. 2014. "Investigating the Safety Effects of Road Width on Urban Collector Roadways." *Safety Science* 62:305–11. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-84885110559&partnerID=40&md5=36fbf3088112a2a5ac1bbb7d0d018440).

4. Russo, Francesca, Mariarosaria Busiello, Salvatore Biancardo A, and Gianluca Dell'Acqua. 2014. "Assessing Transferability of Highway Safety Manual Crash Prediction Models to Data from Italy." *Transportation Research Record: Journal of the Transportation Research Board* (2433):pp 129–35. Retrieved (http://dx.doi.org/10.3141/2433-15).

5. Wood, J. S., J. P. Gooch, and E. T. Donnell. 2015. "Estimating the Safety Effects of Lane Widths on Urban Streets in Nebraska Using the Propensity Scores-Potential Outcomes Framework." *Accident Analysis and Prevention* 82:180–91. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-84935829469&partnerID=40&md5=495655c7fd13a119459db74543220a65).

3.2.2 Selected not coded references

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(https://trid.trb.org/view/353694).

7. Costa, J. O. D., M. A. P. Jacques, P. A. A. Pereira, E. F. Freitas, and F. E. C. Soares. 2015. "Portuguese Two-Lane Highways: Modelling Crash Frequencies for Different Temporal and Spatial Aggregation of Crash Data." *Transport*. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-84939474048&partnerID=40&md5=c92a92195e841f33b9097713e98c949d).

8. Dell'Acqua, Gianluca, Francesca Russo, and Salvatore Antonio Biancardo. 2013. "Risk-Type Density Diagrams by Crash Type on Two-Lane Rural Roads." *Journal of Risk Research* 16(10):1297–1314. Retrieved March 29, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84887014872&partnerID=tZOtx3y1).

9. Ewing, R. and E. Dumbaugh. 2009. "The Built Environment and Traffic Safety: A Review of Empirical Evidence." *Journal of Planning Literature* 23(4):347–67. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-66649089505&partnerID=40&md5=691a16731f6a3d0d3b46ab44c7d5bf70).

10. O'Cinneide, D., Judith Murphy, and Terence Ryan. 2005. "The Effect of Geometric Elements on Interurban Accident Rates." P. 15p in. Retrieved (https://trid.trb.org/view/760498).

11. Othman, Sarbaz and Robert Thomson. 2007. "Influence of Road Characteristics on Traffic Safety." P. 10p in. Retrieved (http://www-nrd.nhtsa.dot.gov/departments/esv/20th/).

12. Kononov, Jake, Barbara Bailey, and Bryan Allery. 2008. "Relationships between Safety and Both Congestion and Number of Lanes on Urban Freeways." Transportation Research Record: Journal of the Transportation Research Board 2083(2083):26–39. Retrieved April 5, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-63849190098&partnerID=tZOtx3y1).

3.2.3 Supporting references

Elvik, R., Hoye, E., Vaa, T., & Sorensen, M. (2009). The Handbook of road safety Measures, 2nd edition. Bingley, UK: Emerald Publishing.

Synopsis 21: Cross-section deficiencies - Narrow lanes

1 Summary

B. Loenis, G. Schermers, J.W.H. van Petegem (SWOV, sept. 2016)

1.1 COLOUR CODE: YELLOW

Research shows that narrow lanes can contribute to either a decrease or increase of crashes. The magnitude of the effect may vary depending on the included covariates and used methods. The degree to which lane width may affect crashes depends upon its interaction with other characteristics of the roadway, specifically, number of lanes and shoulder width. When the variable AADT is taken into account in the model it can be said that it has a negative effect on road safety, whether the individual outcome of the variable narrow lanes is positive or negative.

1.2 KEYWORDS

Narrow lanes, lane width, crashes

1.3 ABSTRACT

Research shows that narrow lanes can have both positive and negative effects on road safety. The effect of a narrow lane on crashes often concerns only the number of crashes or total crash reduction. A distinction between crash types is rarely found. Some studies indicate that narrow lanes lead to a higher number of crashes while other studies reveal an opposite effect. The difference depends on the circumstances and is the interaction with other variables like annual average daily traffic (AADT), road type, shoulder width and the percentage of heavy good vehicles (HGV). Most of the studies involve Crash Prediction Models (CPMs). When the variable AADT is taken into account in the model it can be said that it has a negative effect on road safety, whether the individual outcome of the variable narrow lanes is positive or negative

1.4 BACKGROUND

1.4.1 Definitions of narrow lane

The risk factor narrow lane is defined as a driving lane which has a lane width smaller than the standard lane width and is measured as the distance between lane markings. In the case of two lane roads this would be distance between the edge line and the center line. It is expressed in meters or feet. In most studies specific values, in foot or meter, are given for the width of the lanes. In other studies the presence of a narrow lane is indicated by means of a dummy variable. A dummy variable takes the value of 0 or 1, indicating whether the variable narrow lanes is either present or absent.

1.4.2 How do narrow lanes affect road safety?

The effects of narrow lanes on road safety have been found to be both positive and negative. It is generally assumed that narrow lanes provide less space to drive and therefore less space to correct for driving errors. Narrow lanes force the drivers closer to traffic on the opposing driving lane, increasing frontal and sideswipe crashes. The smaller driving space results in a less forgiving surrounding in which drivers tend to uphold lower driving speeds. Wider lanes on the other hand provide more driving space for drivers. They increase the drivers' sight on the road and make it easier to overtake other traffic. The wider lanes allow for the correction of driving errors and in combination with the increased driver's sight, it will encourage drivers to increase their driving speed. The mentioned effects will not solely depend on the lane width but also on other aspects like road width, the presence and width of a shoulder, the presence and width of a redress lane. The combination of these aspects defines the surroundings through which drivers will pass and on which the drivers will respond.

1.4.3 Which safety outcomes are affected by narrow lanes?

The effects of narrow lanes on road safety have frequently been studied in terms of crash frequency (number of crashes) or crash reduction factors. In some studies a distinction has been made in crash types like head-on and rear-end. Studies seldom mention crash severities and the types of traffic involved. Generally, it is clear that motorized vehicles are included but there is no mention of pedestrians or cyclists.

1.4.4 How is the effect of narrow lanes on crashes studied?

The majority of international literature estimates the effect of narrow lanes by developing Crash Prediction Models (CPMs) or Crash Modification Factors (CMFs) through the application of non-linear regression models or propensity score models. The majority of studies identified the relationship between the number of crashes (dependent variable) and any number of road design and other features (the independent or predictor variables) and often takes the form of (mixed effects) Poisson or Negative Binomial (NB) models

The synopsis focusses on studies conducted between 2010 and 2016 from Italy (2x), USA, Canada and Portugal.

1.5 OVERVIEW RESULTS

A total of 11 studies were selected as candidate studies for coding. Of these only 5 were found to be suitable and provided sufficient methodological detail allowing the effects to be coded. The results of the selected studies are mixed and do not all point in the same direction. The reason for this lies in the differences in the methodological approaches followed and the fact that the multiple regression models used, comprised different sets of dependent and independent variables. Furthermore, the effects were calculated for different (sub) sets of crash data including differences in environmental surroundings (rural, urban), traffic composition (volume of % HGV) and geometrical aspects (divided, undivided and shoulder width). Meta-analysis of these results was therefore not sensible nor advised (Elvik et al, 2009).

Potential transferability of results is questionable, due to the fact that this risk factor has not been investigated under a wide range of conditions. The main restriction is that the vast majority of studies concern regional locations. For these reasons, it was not feasible to produce an overall estimate for the effect of narrow lanes on the number of accidents.

Two of the five studies show a negative effect of narrow lanes on road safety. One of the studies provides a fixed value while for the other the value depends on the amount of AADT. The other three studies show a positive effect of narrow lanes on road safety. For two of these studies the variable narrow lanes and AADT have been combined. The estimate of the interaction effect depends on the volume of traffic, for which high values give a negative effect on road safety and low values give a positive effect.

Overall the studies reveal mixed results. When the variable AADT is taken into account in the model it can be said that it has a negative effect on road safety, whether the individual outcome of the variable narrow lanes is positive or negative.

1.6 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound. Most of the studies are based on statistical regression models using different sets of dependent and independent variables. The studies mainly focus on regional networks with specific characteristics and limited available data which make it difficult to estimate the reliability of the results and the possibility for comparison. Moreover, the effect has not been tested under the same or under all conditions and more studies are needed. Overall, the topic has not been deeply studied. Because of the fact that the study designs, the applied methods and input data are somewhat heterogeneous and inconsistent, potential transferability of results is unlikely.

2 Scientific overview

2.1 LITERATURE REVIEW

The literature review is based on the 5 coded studies from the literature search. 5 studies were selected for coding on the basis of being the most recent, relevant (in terms of reported effects of narrow lanes on road traffic crashes) and published in recognized scientific journals. All of these studies were coded.

All five studies investigated crash frequency (number of accidents) of all severities due to narrow lanes. One of these studies specified the crash frequencies further to crash types (total, injury, head-on, side-swipe and rear-end) and crash severities (injurious and fatal). The five investigated studies propose a Crash Prediction Model (CPM), a Safety Performance Function (SPF) or a Crash Modification Factor (CMF).

A paper by Russo et. al (2014) uses the prediction methodology proposed by the Highway Safety Manual and includes a SPF to predict the total crash frequency for road segments meeting the base conditions. The base condition for lane width is 12 ft (3,6 m) and a crash modification factor (CMF) is defined for the alternative lane widths of < 9 ft (2,7 m), 10 ft (3,0 m) and > 11 ft (3,3 m). The comparison is made for three levels of AADT, in which the CMFs increase when the AADT decreases. The results show that all CMFs are larger than one, implying that narrow lanes lead to more crashes. Comparing the CMFs of the three narrow lane widths gives mixed results. It is unclear whether narrower lanes have a positive or negative effect on the number of crashes compared to a less narrow lane. For example, when the effect of a road segment with a lane width of 9 ft (2,7 m) is compared to a road segment with a lane width of 11 ft (3,3 m).

A paper by Da Costa et. al (2016) presents a CPM for the expected number of crashes, using the generalized estimating equations (GEE) with a negative binomial link function. CPMs were developed for multiple time periods and road segments of 200 and 400 meters length. For road segments of 200 meters the variable narrow lanes was found to not have a significant effect on crashes in any of the defined time periods. For road segments of 400 meters the variable narrow lanes was found to have a significant effect, with a positive coefficient. All significant coefficients were positive, implying an increase of the number of crashes. The best model fit was found for segments of 400 meters and a time period of 6 years.

A paper by Dell'Acqua et. al (2010) predicts the number of crashes by means of a multiple variable non-linear regression method based on the least squares method. Two prediction models were developed: one for multilane divided roadways and one for major and minor undivided two-lane rural roads. The model for the multilane roadways was not able to find a significant contribution of the lane width variable. The model for the two-lane rural roadways found a negative coefficient for the narrow lane variable, implying a decrease in the number of crashes with increased lane width.

A paper by Wood et. al (2015) presents CMFs for various urban lane widths by using the propensity scores-potential outcomes framework. CMF estimations were made using a mixed-effects negative binomial or Poisson regression. Six comparisons were made for the variable lane width: 9 ft (2,7 m) vs 12 ft (3,6 m), 10 ft (3,0 m) vs 12 ft (3,6 m), 11 ft (3,3 m) vs 12 ft (3,6 m), 9 ft (2,7 m) vs 11 ft (3,3 m), 10 ft (3,0 m) vs 11 ft (3,3 m) and 9 ft (2,7 m) vs 10 ft (3,0 m). For each comparison a distinction in crash type was made: total, injury, head-on, sideswipe-same, sideswipe-opposite and rear-end.

Coefficients were given for the narrow lane variable but also for the interaction variable of Narrow lane*AADT. The effect of the single variable narrow lane leads to mixed effects, while the addition of the AADT almost always leads to more crashes for higher traffic flows. 9 ft (2,7 m) lane segments have a lower expected crash frequency than other lane widths, except for the low-volume 12 ft (3,6 m) lanes, probably because they have very little or no heavy vehicle traffic and represent minor arterials and collectors with lower speed limits. The expected crash frequency of roads with 10 ft (3,0 m) lanes is higher than all roads with other lane widths. Roads with 11 ft (3,3 m) lanes are associated with increased crash frequency when compared to 12 ft (3,6 m) lanes at high traffic volumes. The CMFs estimated for sideswipe crashes were greater than one in almost all scenarios, probably because there is less space between opposite traffic flows on narrow lanes. However, coefficients of sideswipe crashes are often insignificant. For fatal and injurious crashes the significant coefficients were negative, implying a decrease in the number of fatal and injurious crashes. The significant effects of head-on and rear-end crashes are limited and show mixed results.

A study by Manuel et. al (2013) presents negative binomial safety performance functions (SPFs) for the total number of crashes. In the study two-lane urban collectors with oversized roads segments (total road width > 14 m) are matched with standard road segments (total road width < 11,5 m). The presence of oversized road segments shows a negative coefficient, implying that fewer crashes occur on oversized road segments compared to standard road segments. The effect of the presence of an oversized road in combination with traffic volume has also been studied. The results show a positive coefficient, implying an increasing number of crashes for an increasing volume of daily traffic on oversize roads. For traffic volumes lower than 4.000 vehicles per day, road segments with oversized lane widths tend to have fewer crashes compared to road segments with standard lane widths. For traffic volumes higher than 4.000 vehicles per day, road segments with oversized lane widths tend to have more crashes compared to road segments with standard lane widths.

2.2 ANALYSIS METHODS AND RESULTS

2.2.1 Introduction

The effects of narrow lanes can be summarized as follows:

- 1 study with an increase of crash frequency for narrow lanes, no statistical tests performed (+)
- 1 study with a significant increase of crash frequency for narrow lanes (+)
- 1 study with a significant decrease of crash frequency for narrow lanes (-)
- 1 study with a significant limited increase of crash frequency for small lane width reductions (+) and a significant decrease of crash frequency for larger lane width reductions (-)
- 1 study with a significant increase of crash frequency for narrow lanes with low traffic volumes (-) and a significant decrease of crash frequencies for narrow lanes with high traffic volumes (+)

Table 1 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 1 Description of coded studies

Author(s), Year	Sample and study design	Method of analysis	Outcome indicator	Main result
Russo et al (2014)	2121 crashes from 2003 to 2010, covering almost 3600 km and involving 2297 injuries and 80 deaths.Observational, cross-sectional study incorporating regression modelling	Base regression model	Number of crashes	Narrow lanes lead to a significant increase of crashes. CMFs range from 1,10 up to 3,30.
Da Costa et al (2016)	1056 records of 200 meter segments and 384 records of 400 meter segments for the years 1999 to 2010. Data includes the number of fatalities and injury crashes, volume and geometric characteristics. Observational, cross-sectional study incorporating regression modelling	Generalized linear model	Number of crashes	Narrow lanes lead to a significant increase of crashes.
Dell'Acqua et. al (2010)	Approximately 700 records of accidents between 2003 and 2005, including AADT and roadway characteristics. Observational, cross-sectional study incorporating regression modelling	Generalized linear model	Number of crashes	Narrow lanes lead to a significant reduction in the number of crashes.
Wood et al (2015)	18227 observations at midblock segments on urban streets in four Nebraska cities. Reported data includes: crash frequency, crash severities, crash types, AADT and roadway characteristics. Observational, cross-sectional study.	Propensity scores-potential outcomes framework	Number of crashes per crash type (total, injury, head-on, sideswipe and rear-end)	Limited increase of crashes for small lane width reductions, significant decrease of crashes for larger lane width reductions
Manuel et al (2013)	106 oversized road segments and 106 standard sized road segments with data on crashes, traffic-volume and roadway features between 2006-2010. Observational and cross-sectional study incorporating regression modelling	Negative Binomial models	Number of crashes	Wider lanes lead to less crashes for low traffic volumes and lead to more crashes for high traffic volumes.

The results of the coded studies are mixed. Furthermore, the effects are based on predominantly multiple regressions using different sets of variables and different models whereby the results do not lend themselves for meta-analysis.

2.2.2 Overall estimate for accident severity

Not all of the coded studies correct for exposure and the estimates are subject to different models with different sets of dependent and independent variables and therefore the estimates are not directly comparable. When a study investigates the effect of narrow lanes for varying quantities of AADT, the results show an increase of crashes for low traffic volumes. For high traffic volumes the increase is lower or can lead to a decrease of crashes for narrow lanes. Estimations solely based on the risk factor narrow lane give mixed results and depend a lot on the independent variables which are used. For example, road width, redress lane width, road type, percentage of HGV, shoulder width etc.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature search aimed at identifying the highest quality and most recent studies for quantifying the relationship between narrow lane and crash occurrence (number of crashes) and crash severity. Therefore the document search strategy was primarily aimed at studies undertaken in Europe and published in recognized scientific journals and publications. Failing that, the search fell back on older studies and/or studies from other parts of the world but with the provison that these were published in recognized scientific publications. The Scopus and TRID databases were searched in the formal literature search. All searches were filtered on English results only. The literature search was done in 2016.

To select papers relating to road safety in Scopus, the following query is used: ((road and casualt*) or (road and injur*) or (road and accident*) or (road and crash*) or (traffic and injur*) or (traffic and casualt*) or (traffic and accident*) or (traffic and crash*)).

To select papers relating to road safety in TRID, the following query is used: (collision* or crash* or accident* or injur* or casualt*) AND (traffic or road).[1]

The aforementioned queries were combined with a query to select papers relating to the risk factor narrow lane: "narrow lane" or "narrow lanes" or "lane width" or "width of the lane" or "lane widths" or "width of the lanes" or "widths of the lanes").

These queries were combined in Scopus and TRID to search for literature about the risk factor narrow lane. To distinguish literature from Europe and Worldwide, the results were loaded into Mendeley, where the following query was used to identify literature from Europe: (Italy or Ireland or Hungary or Greece or Germany or France or Finland or Estonia or Denmark or Czech or Cyprus or Croatia or Bulgaria or Belgium or Austria or Scotland or England or Britain or United Kingdom or Sweden or Spain or Slovenia or Slovakia or Romania or Portugal or Poland or Netherlands or Malta or Luxembourg or Lithuania or Latvia).

The number of hits for Europe and Worldwide and for Scopus and TRID are presented in table 1.

Table 1 Literature search strategy

search no.	Region	Database	hits
#1	Europe	Scopus	36
#2	Europe	TRID	50
#3	Worldwide	Scopus	124
#4	Worldwide	TRID	372

[1] The difference in the queries is due to differences in restrictions to the query length between the two sources.

Following the initial selection of relevant publications, a new selection of publications was made in Mendeley, sorting the publications on year and source. Only publications from trusted sources and most recent publications were selected with a maximum number of about 80. From this selection all abstracts were reviewed. From reviewing the abstracts a total of 11 publications were selected as the most promising. For 3 of these the full text version could not be retrieved and these were not considered further. The remaining 8 publications were reviewed and 1 of these was judged unsuitable for coding (specific effect not reported, topic not specifically addressed etc.).

The final studies selected for the topic narrow lanes suggest that although this topic has been studied in some depth, the study methodologies and subsequent results are diverse and mixed. No meta-analyses were found on this topic and the literature review reveal that the results of the selected five studies do not lend themselves for inclusion in a meta-analysis. The majority of these studies are based on multiple regression models using different dependent and independent variables and with widely varying outcomes.

3.2 LIST OF STUDIES

A detailed list of studies considered (and of which the first 5 were selected for coding) are listed below:

3.2.1 Coded studies

Costa, J. O. D., M. A. P. Jacques, P. A. A. Pereira, E. F. Freitas, and F. E. C. Soares. 2015. "Portuguese Two-Lane Highways: Modelling Crash Frequencies for Different Temporal and Spatial Aggregation of Crash Data." *Transport*. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-84939474048&partnerID=40&md5=c92a92195e841f33b9097713e98c949d).

Dell'Acqua, Gianluca and Francesca Russo. 2010. "Accident Prediction Models for Road Networks." P. 11p in. Retrieved (https://trid.trb.org/view/1100358).

Manuel, Aaron, Karim El-Basyouny, and Md. Tazul Islam. 2014. "Investigating the Safety Effects of Road Width on Urban Collector Roadways." *Safety Science* 62:305–11. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-84885110559&partnerID=40&md5=36fbf3088112a2a5ac1bbb7d0d018440).

Russo, Francesca, Mariarosaria Busiello, Salvatore Biancardo A, and Gianluca Dell'Acqua. 2014. "Assessing Transferability of Highway Safety Manual Crash Prediction Models to Data from Italy." *Transportation Research Record: Journal of the Transportation Research Board* (2433):pp 129–35. Retrieved (http://dx.doi.org/10.3141/2433-15).

Wood, J. S., J. P. Gooch, and E. T. Donnell. 2015. "Estimating the Safety Effects of Lane Widths on Urban Streets in Nebraska Using the Propensity Scores-Potential Outcomes Framework." *Accident Analysis and Prevention* 82:180–91. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-84935829469&partnerID=40&md5=495655c7fd13a119459db74543220a65).

3.2.2 Not coded selected studies

BRANNOLTE, U. 1990. "EVALUATION AND COMPARISON OF TRAFFIC SAFETY ON HIGH STANDARD RURAL ROADS." *VTI Rapport* (351A):p. 211–24. Retrieved (https://trid.trb.org/view/353694).

Costa, J. O. D., M. A. P. Jacques, P. A. A. Pereira, E. F. Freitas, and F. E. C. Soares. 2015. "Portuguese Two-Lane Highways: Modelling Crash Frequencies for Different Temporal and Spatial Aggregation of Crash Data." *Transport*. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-84939474048&partnerID=40&md5=c92a92195e841f33b9097713e98c949d).

Dell'Acqua, Gianluca, Francesca Russo, and Salvatore Antonio Biancardo. 2013. "Risk-Type Density Diagrams by Crash Type on Two-Lane Rural Roads." *Journal of Risk Research* 16(10):1297–1314. Retrieved March 29, 2016 (http://www.scopus.com/inward/record.url?eid=2-s2.0-84887014872&partnerID=tZOtx3y1).

Ewing, R. and E. Dumbaugh. 2009. "The Built Environment and Traffic Safety: A Review of Empirical Evidence." *Journal of Planning Literature* 23(4):347–67. Retrieved (http://www.scopus.com/inward/record.url?eid=2-s2.0-66649089505&partnerID=40&md5=691a16731f6a3d0d3b46ab44c7d5bf70).

O'Cinneide, D., Judith Murphy, and Terence Ryan. 2005. "The Effect of Geometric Elements on Interurban Accident Rates." P. 15p in. Retrieved (https://trid.trb.org/view/760498).

Othman, Sarbaz and Robert Thomson. 2007. "Influence of Road Characteristics on Traffic Safety." P. 10p in. Retrieved (http://www-nrd.nhtsa.dot.gov/departments/esv/20th/).

3.2.3 Supporting references

Elvik, R., Hoye, E., Vaa, T., & Sorensen, M. (2009). The Handbook of road safety Measures, 2nd edition. Bingley, UK: Emerald Publishing.

Synopsis 22: Undivided Road

1 Summary

Usami, D. S., August 2016

1.1 COLOUR CODE: YELLOW

Undivided roads seem to increase the severity of head-on road crashes. However the effects seem to depend to the type of crash investigated and various external factors (e.g. type of area, road alignment).

1.2 KEYWORDS

Undivided road; median; central reservation; single carriageway; head-on crashes

1.3 ABSTRACT

In general, mixed effects of undivided road on road safety are observed. The identified studies examine the effect of the absence/presence of a median included as a variable in multivariable linear statistical models. Undivided roads appear to not have a significant effect on head-on crashes frequency, but increase their severity. Severity of run-off-road (ROR) and pedestrian crashes seems not to be affected, but the number of ROR crashes appears to decrease. Transferability issues may arise as different type of crashes are examined under different conditions.

1.4 BACKGROUND

What is undivided road?

An undivided road is a road with one or more lanes arranged within a single carriageway, without any physical separation between traffic streams (median or central reservation). In contrast a divided road is a road in which the two directions of traffic are separated by a median or a central reservation.

How does undivided road affect road safety?

Undivided roads may have both increasing or decreasing effect on risk of crash. The absence of a median decreases the distance between opposing traffic flows which may result in a higher number of head-on collisions, but may reduce the number of less severe crashes (Elvik et al., 2009). Undivided roads may increase the number of turning vehicles thus possible conflicts between turning and oncoming traffic. In addition, pedestrians' exposure to traffic when crossing the road may also increase. Undivided roads may reduce crash frequency in curves probably because of more space available to recover the vehicle in case of running off the road.

However, there is limited information available regarding the effect of undivided roads on road crash occurrence and severity.

Which safety outcomes are affected by undivided road?

In the international literature, the effect of undivided roads on road safety has been measured using two basic outcomes, namely crash frequency (number of crashes occurred) and crash severity (severity of injuries of occupants given that a crash has occurred).

How is the effect of undivided roads studied?

International literature indicated that the effect of undivided roads is usually examined by applying multivariable linear statistical models. In crash frequency models, the relationship between the presence of a median and the number of crashes is investigated with e.g. negative binomial models, while in crash severity models, the considered studies usually apply logistic regression or probit models.

Which factors influence the effect of undivided road on road safety?

Road horizontal alignment and speed may influence the effect of undivided roads on road safety. Travelling too fast in curves may lead to a vehicle leaving its own lane with the risk of a head-on collision with oncoming traffic. Although speed is not directly considered in relation to the absence of a median in most of the studies, it is obvious that the higher the vehicle speeds the more severe are head-on collisions. Different road classes are usually designed with different standards (number of lanes, road width, curve radius, etc.) and equipped with different median types (for instance, grass medians, Jersey barriers, and guardrails are more common on faster roads). This means that road classification may also affect number, type and severity of crashes on undivided road.

Other factors, such as the number of pedestrians attempting to cross the road may influence the effect of undivided road on other type of crashes (e.g. pedestrian crashes).

Age, gender and other road user related factors seem not to affect the effect of undivided road.

1.5 OVERVIEW RESULTS

According to results in the identified studies, the effect of an undivided road on road safety is not so clear. One study on crash frequency shows that undivided roads appear to lead to a lower number of single vehicle crashes. A possible reason is that on divided roads there are more objects for vehicles to collide with (e.g. safety barriers on both sides of the roadway). Another study reported that undivided roads tend to not have a significant effect on head-on crashes frequency. When coming to crash severity, it was found that the presence of a median seems not to have any significant effects on the severity of single vehicle crashes and pedestrian crashes. While it was found that the presence of median reduced the probability of severe head-on crashes.

The studies identified are from Australia, Malaysia and the US. However, potential transferability of results is questionable, due to the fact that the examined studies analyse different type of crashes (head-on crashes, pedestrian crashes, single vehicle crashes) on different road network (urban area only, mostly rural and suburban area, all type of roads), so that there is a lack of studies with similar results starting from the same conditions.

Since there was no meta-analysis obtained during the literature search the conclusions are based on the studies presented in the reference list.

1.6 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound.

Overall, the number of relevant studies is quite small (only 3). The risk factor has been tested in three different countries, however because of the fact that the study designs, the applied methods and the sampling frames are somewhat variable and inconsistent, potential transferability of results is unlikely. In general, more studies are needed, exploring more deeply this risk factor under various conditions but similar modelling approaches and indicators.

2 Scientific overview

2.1 LITERATURE REVIEW

Undivided roads affect especially head-on crashes, when a vehicle crosses the centreline of the road to collide with an oncoming vehicle. By introducing a median the distance between opposing traffic flows increases, which may result in a lower number of head-on collisions, but appear to increase the number of less severe crashes (Elvik et al., 2009). Most of the research focused on the effect of the introduction of medians as a measure to reduce crashes, however few studies was found to investigate the risk of undivided roads compared to divided roads.

According to the results in the identified studies, the effect of an undivided road on road safety is not so clear. A Malaysian study reported that undivided roads tend to not have a significant effect on head-on crashes frequency (Hosseinpour et al., 2013). However, according to an Australian study (Stephan and Newstead, 2011), undivided roads appear to lead to a lower single vehicle crash number in urban area. The reason for this is not clear, perhaps on divided roads there are more objects for vehicles to collide with (e.g. safety barriers on both sides of the roadway).

Undivided roads may reduce crash frequency in curves probably because of more space available to recover the vehicle in case of crossing the centre line (Elvik et al., 2009).

In urban area, undivided roads may affect the number of turning vehicles thus increasing the number of conflicts between turning and oncoming traffic. In addition, pedestrian exposure to traffic when crossing the road may also increase.

On rural roads, where generally speeds are higher than urban roads, head-on crashes result in serious injury outcomes. This is confirmed by Hosseinpour et al. (2013) who found that the absence of a median increased the probability of severe head-on crashes. The presence of a median seems not to have any significant effects on the severity of single vehicle crashes (Stephan and Newstead, 2011) and pedestrian crashes (Hanson et al., 2013).

2.2 DESCRIPTION OF AVAILABLE STUDIES

Analysis of study designs and methods

There has been some research completed on the presence/absence of median and its implication on road safety. 3 studies were selected and coded. 2 of the studies investigated the effects on crash frequency (Hosseinpour, et al., 2013; Stephan and Newstead, 2014) and 3 on crash severity (Hanson et al., 2013; Hosseinpour, et al., 2013; Stephan and Newstead, 2014). In order to examine the relationship between presence/absence of median and outcome indicators, 2 studies used a cross sectional design and one study a case-control design.

All studies deployed multivariate statistical models (i.e. Poisson, negative binomial models, etc.) as a method of examining the topic and controlled for other geometrical characteristics and traffic flow.

Studies on crash frequency used Poisson and random-effect negative binomial regression models (Hanson et al., 2013; Hosseinpour, et al., 2013). Crash severity was modelled through logistic regression models (Hanson et al., 2013; Stephan and Newstead, 2014) and a random-effect generalized ordered probit model.

The studies identified focused on rural, suburban roads (Hosseinpour, et al., 2013), urban roads (Stephan and Newstead, 2011) and all roads (Hanson et al., 2013). Hanson et al., (2013) investigated pedestrian crashes, Hosseinpour, et al., (2013) focused on head-on crashes, while Stephan and Newstead (2014) analysed single vehicle crashes.

Table 1 illustrates an overview of the main aspects of coded studies (sample, method, outcome and results).

Table 1 Description of coded studies

Author(s), Year , Country	Sample and study design	Method of analysis	Outcome indicator	Main result
Hanson et al., 2013, US	2351 pedestrian crashes. A case-control methodology is used.	Two binary logistic regression models	Odds for killed and Odds for Killed or incapacitated pedestrians	There is no basis from these results to show any effect of undivided roads on crash severity.
Hosseinpour et al., 2013, Malaysia	A total of 527 head-on crashes that occurred on 448 segments of five federal roads in Malaysia considered	Random-effect negative binomial model (to assess crash frequency). Random-effect generalized ordered probit model (to assess crash severity)	Head-on crash frequency; Probability of being slightly, seriously or fatally injured	Undivided road does not contribute significantly to head-on crashes frequency, but has a negative effect on the injury level.
Stephan and Newstead, 2014, Australia	142 metropolitan strip shopping centre road segments located in Australia. Between 2005 and 2009, 170 single vehicle crashes occurred on the road segments of interest	Poisson regression models used to identify factors associated with single vehicle crashes frequency. Logistic regression used to determine factors associated with serious and fatal outcomes.	Single vehicle Crash frequency (number of crashes) and Probability of being killed or seriously injured	The absence of a median of any length on the road segment was associated with a decrease in single vehicle crash frequency

2.3 RESULTS

The studies identified show that the absence of medians may lead to both positive and negative effects on road safety, according to the target crash and the specific context examined.
Hanson et al. (2013) investigated the effects of undivided roads on pedestrian crashes per different road classes by studying the interaction effect with the number of lanes of a roadway. However, they came to the conclusion that there is no basis from their results to show any effect of medians on pedestrian crashes severity. Hosseinpour et al. (2013) indicates that the presence of a median does not contribute significantly to head-on crashes frequency, however they found that the presence of median reduced the probability of severe crashes. Stephan and Newstead (2014) analysed the effect of undivided road on single-vehicle crash frequency and severity in complex urban environments, namely, strip shopping centre road segments. They found that the presence of a median of any length was associated with an increase in single-vehicle crash frequency but had no significant effect on severity of single vehicle crashes.

A meta-analysis cannot be carried out because a minimum required number of studies (3) is not achieved, in particular:

a) At least 3 studies did not use the same model form
b) The sampling frames were different in all cases

Table 2 presents information on the main outcomes of coded studies on undivided road.

Table 2 Main outcomes of coded studies for undivided road

Author, Year, Country	**Exposure variable**	**Outcome variable / Outcome type**	**Effects***		**Main outcome -description**
Hanson et al., 2013	Two or fewer lanes, median	Probability of pedestrian fatal versus injury-only outcomes	-	0,718	Non-significant effect on road safety**
	Three lanes, median	Probability of pedestrian fatal versus injury-only outcomes	-	0,668	Non-significant effect on road safety**
	Four or five lanes, median	Probability of pedestrian fatal versus injury-only outcomes	-	1,268	Non-significant effect on road safety**
	Six or more lanes, median	Probability of pedestrian fatal versus injury-only outcomes	↗	1,941	Crashes on roads with six or more lanes and median are significantly more likely to be fatal than crashes on roads with two or fewer lanes and no median. However there is really no basis from these results to show any effect of medians on crash severity. **
	Two or fewer lanes, median	Probability of pedestrian fatal or incapacitated versus less severe injury outcomes	-	1,014	Non-significant effect on road safety**
	Three lanes. median	Probability of pedestrian fatal or incapacitated versus less severe injury outcomes	-	1,001	Non-significant effect on road safety**
	Four or five lanes, median	Probability of pedestrian fatal or incapacitated versus less severe injury outcomes	-	1,155	Non-significant effect on road safety**
	Six or more lanes, median	Probability of pedestrian fatal or incapacitated versus less severe injury outcomes	↗	1,420	Crashes on roads with six or more lanes and median are significantly more likely to be fatal or incapacitated than crashes on roads with two or fewer lanes and no median. However there is really no basis from these results to show any effect of medians on crash severity. **
Hosseinpour et al., 2013	Presence of Median	Probability of slight injury	↗	-1,108	Undivided roads (absence of median) increases the probability of slight injuries in head-on crashes
	Presence of Median	Probability of serious injury	↗	−0,865	Undivided roads (absence of median) increases the probability of severe injuries in head-on crashes

	Presence of Median	Probability of fatal injury	↗	-0,250	Non-significant effect on road safety
	Presence of Median	Head-on crash frequency	-		Non-significant effect on road safety*
Stephan & Newstead, 2014	Presence of Median	Single vehicle crash frequency	↘	1.820	Undivided roads (absence of median) decrease single vehicle crash frequency
	Presence of Median	Probability of being killed or seiously injured	-		No significant effect.

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)
** Presence of median does not contribute significantly to head-on crashes frequency, therefore it was not included in the model

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature search was conducted in March-April and August 2016. The search strategy aimed at identifying the best quality and recent studies to estimate the effect of this risk factor. In general, only recent journal studies (after 1989) in the field of Engineering and Social science were initially considered from "Scopus" and "TRID" database. Search terms used to identify relevant papers included but were not limited to: "Undivided road". Detailed search terms, as well as their linkage with logical operators and combined queries are shown in Tables 3 and 4. A total of 95 pieces of potentially eligible studies were identified. After a preliminary abstract screening text 5 were found to be mostly relevant to the topic. However, after a full-text screening all the 5 papers were judged unsuitable for coding (specific effect not reported, topic not specifically addressed etc.).

A second search strategy on Scopus database was then adopted by changing the search terms (i.e. "Presence of median") and leading to 5 potentially eligible studies (Table 6). After a full-text screening 3 studies was coded and included in the synopsis (the other 2 studies were judged unsuitable for coding).

Table 3 Literature search strategy **(Scopus database) - Date:** 30th of March 2016

search no.	search terms / operators / combined queries	hits
#1	"Undivided road" AND DOCTYPE (ar OR re) AND PUBYEAR > 1989 AND SRCTYPE (j) AND LANGUAGE (english) AND SUBJAREA (engi OR soci)	24
#2	("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "risk") AND DOCTYPE (ar OR re) AND PUBYEAR > 1989 AND SRCTYPE (j) AND LANGUAGE (english) AND SUBJAREA (engi OR soci)	3,012,662
#3	#1 AND #2	**45**

Table 4 Literature search strategy **(TRID database)- Date:** 20th of April 2016

search no.	search terms / operators / combined queries	hits
#1	undivided road risk accident	50

Table 5 Literature search strategy **(Scopus database)- Date:** 20th of August 2016

search no.	search terms / operators / combined queries	hits
#1	"presence of median" AND DOCTYPE (ar OR re) AND PUBYEAR > 1989 AND SRCTYPE (j) AND LANGUAGE (english) AND SUBJAREA (engi OR soci)	7
#2	("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "risk") AND DOCTYPE (ar OR re) AND PUBYEAR > 1989 AND SRCTYPE (j) AND LANGUAGE (english) AND SUBJAREA (engi OR soci)	450,492
#3	#1 AND #2	**5**

The final 3 studies included in the synopsis indicate that the topic has not been thoroughly investigated. No "grey" literature was examined. No meta-analyses were found.

3.2 LIST OF STUDIES

A detailed list of studies considered are listed below:

Hanson Christopher S., Robert B. Noland,Charles Brown. The severity of pedestrian crashes: an analysis using Google Street View imagery. (2013) Journal of Transport Geography. Volume 33, December 2013, Pages 42–53 http://dx.doi.org/10.1016/j.jtrangeo.2013.09.002

Hosseinpour Mehdi, Ahmad Shukri Yahaya, Ahmad Farhan Sadullah. Exploring the effects of roadway characteristics on the frequency and severity of head-on crashes: Case studies from Malaysian Federal Roads (2013). Accident Analysis & Prevention. Volume 62, January 2014, Pages 209–222. http://dx.doi.org/10.1016/j.aap.2013.10.001.

Stephan Karen L. & Stuart V. Newstead. Characteristics of the Road and Surrounding Environment in Metropolitan Shopping Strips: Association with the Frequency and Severity of Single-Vehicle Crashes. (2014). Traffic Injury Prevention 15, S74–S80. http://dx.doi.org/10.1080/15389588.2014.930450. Abdel-Aty M.A., Radwan A.E., (2000). Modeling traffic accident occurrence and involvement. Accident Analysis and Prevention Voume 32, Pages 633–642

3.3 REFERENCES ON FURTHER BACKGROUND INFORMATION

Elvik, R.; Høye, A.; Vaa, T.; Sørensen, M. (2009): The Handbook of Road Safety Measures. Second edition. Emerald Group. Bingley

Björnstig, U., Björnstig, J., Eriksson, A. Passenger car collision fatalities - with special emphasis on collisions with heavy vehicles 2008 Accident Analysis and Prevention, 40 (1), pp. 158-166.

Praticò, F.G., Giunta, MSafety evaluation: A new operating speed model for two-lane, undivided rural roads, 2014, Advances in Transportation Studies, 34, pp. 67-80.

Ydenius, A Frontal crash severity in different road environments measured in real-world crashes 2009 International Journal of Crashworthiness, 14 (6), pp. 525-532.

Carrigan, Christine E; Ray, Malcolm H; Johnson, T Olaf. Run-off-Road Crash Prediction Models for Each Edge of Undivided and Divided Roadways 2015 Transportation Research Board 94th Annual Meeting, Transportation Research Board, 15p.

Preusser, D.F., Williams, A.F., Ulmer, R.G Analysis of fatal motorcycle crashes: crash typing 1995 Accident Analysis and Prevention, 27 (6), pp. 845-851

Synopsis 23: Cross-section deficiencies - Narrow Median

1 Summary

Usami, D. S., August 2016

1.1 COLOUR CODE: YELLOW

Most of the studies show that narrow medians seem to increase the number of crashes. However a study found also that narrow medians tend to have lower no-injury crash rates. Another study came to the conclusion that the effect on injury severity of bus crashes is not significant. Overall, it can be concluded that narrow medians are probably risky.

1.2 KEYWORDS:

Median width; central reservation; narrow median, crash frequency; crash severity

1.3 ABSTRACT

Estimates are based on studies that examine the relationship between median width and both frequency and severity of crashes. It appears that the decrease in median width increases crash frequencies. The effect seems to be more pronouced for crash involvement of female and older drivers. However if median width is less than 40 feet (12 m) the no-injury crash rate appears to decrease. A non-significant effect on injury severity of bus crashes has been found. All studies are from the US.

1.4 BACKGROUND

1.4.1 What is narrow median?

A median is a physical separation between opposing traffic streams. Medians can be paved or landscaped areas. A narrow median is related to "median width", a numerical variable usually measured in meters or feets. There are no commonly adopted thresholds identifying narrow medians. In some cases a reference can be found in the road standards adopted in a country.

1.4.2 How does narrow median affect road safety?

Medians are used for traffic separation. Additional benefits from medians include:

- the provision of recovery area for errant drivers,
- accommodation of left-turn movements into/out of side streets,
- the provision for emergency stopping,
- the provision, in urban area, of a refuge for pedestrians crossing the road.

Narrow medians may represent a safety issue for drivers loosing control of the vehicle as there is less space available for recovery. They also may affect left turning vehicles, as they result poorly protected from ocoming traffic during a two stages left turn. Moreover, narrow medians can be difficult to see, especially at night and in inclement weather. However, there is limited information available regarding the effect of narrow medians on road crash occurrence and severity.

1.4.3 Which safety outcomes are affected by median width?

In the international literature, the effect of narrow medians on road safety has been measured on two basic outcomes, namely crash frequency (number of crashes occurred) or crash severity (severity of injuries of occupants given that a crash has occurred). The use of crash rate (crashes per 100-million vehicles miles travelled) has been also observed.

1.4.4 How is the effect of narrow median studied?

International literature indicated that the effect of narrow median is usually examined by applying multivariable linear statistical models. In crash frequency models, the relationship between median width and number of crashes is investigated with negative binomial models, whereas in crash severity models, all studies identified applied logistic regression models. Crash rates are explored with multivariate tobit models.

1.4.5 Which factors influence the effect of narrow median on road safety?

Age and gender seem to have an influence on the effect of median width. Older drivers appear to experience higher probability of crashes than middle and young drivers when the median is narrow. The same applies for female drivers compared to male drivers.

1.5 OVERVIEW RESULTS

Most of the studies indentified show that a narrow median appears to have negative effects on road safety. Studies on crash frequency (the most common approach) show that narrow medians appear to lead to a higher crash risk. However, one study reported that narrow medians (less than 40 ft) tend to decrease no-injury crash rate. A possible explanation is that narrow medians tend to be treated with safety barriers When coming to crash severity available results are poor, only one study found that decreased median width leads to non significant effect on crash severity in crash involving buses.

Potential transferability of results is questionable, due to the fact that the vast majority of studies concern regional locations in the United States (e.g. Florida) and is maybe linked with national specifications.

Since there was no meta-analysis obtained during the literature search the conclusions are based on the studies presented in the reference list.

1.6 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodogically sound.

Overall, the topic has not been deeply studied (number of relevant studies is 4). Because of the fact that the study designs, the applied methods and the road user groups of interest are somewhat variable and inconsistent, potential transferability of results is unlikely. Moreover, the effect has not been tested under all conditions (e.g. investigation of crash frequency by different user groups, different road area, no European studies found, etc.) and more studies on crash frequency are needed, since only two relevant studies were found for different road user groups. Summarizing, different modeling approaches and different indicators were found to lead to inconsistent results and for that reason the effect is unclear and needs further examination.

2 Scientific overview

2.1 LITERATURE REVIEW

The effect of narrow median is generally estimated from multivariate crash prediction models including median width as a predictor and any additional independent variables (such as traffic volume, posted speed limit, lane width, number of lanes, etc.). Reducing median width seems to increase crash frequency in rural areas. Wider medians allow uncontrolled vehicles to recover without crossing over to the other side of the road and then onto the other side shoulder. They also may affect left turning vehicles, as they result poorly protected from ocoming traffic during a two stages left turn. Moreover, narrow medians can be difficult to see, especially at night and in inclement weather.

Harkey et al. (2008) developed various crash prediction models to assess the effect of median width on all crashes and cross median crashes under different conditions: the number of lanes, the area type (rural or urban), and the type of control of access. For all the models the results indicated that as median width increases, total crashes and cross median crashes decrease. Median width has a larger effect on cross median crashes compared to total crashes.

Anastasopoulos et al. (2012) found that if median width is less than 40 ft (12 meters) the number of no injury crash per 100-million vehicle-miles of travel (VMT) is expected to decrease. The explanation provided is that typically, narrow (less than 40 ft) medians are treated with safety barriers, and because median slopes become flatter as the median width increases, "the median width variable may be capturing the effect of segments with slopes that are flat enough to prevent severe overturning accidents but do not have adequate median widths to prevent severe median crossover accidents" (Anastasopoulos et al., 2012).

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

There has been some research completed on median width and its implication on road safety. 5 high quality studies were selected and coded. 5 of the studies investigated the effects on crash frequency (Anastasopoulos et al., 2012; Abdel-Aty and Radwan, 2000; Chimba et al., 2010; Jiang et al., 2013; Lee and Mannering, 2002) and 1 on crash severity (Chimba et al., 2010). In order to examine the relationship between median width and outcome indicators, all studies deployed multivariate statistical models (i.e. negative binomial, generalized estimating equation models, etc.) as a method of examining the topic and controlled for other geometrical characteristics and traffic flow as well.

Studies on crash frequency used mostly negative binomial regression models (Abdel-Aty and Radwan, 2000; Chimba et al., 2010) or derived models such as one random effect negative binomial model (Jiang et al., 2013) and zero-inflated negative binomial model (Lee and Mannering, 2002). The study on crash severity (Chimba et al., 2010) used a multinomial logit model. Anastasopoulos et al. (2012) investigated the effect on crash rates categorized by injury severities with a multivariate tobit model.

The studies identified focused on highways with 1 to 5 lanes per direction. Studies focused on motor vehicle crashes. Chimba et al., (2010) analysed crashes involving buses. All research has been done in the United States.

Table 2 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 2 Description of coded studies

Author(s), Year, Country	Sample and study design	Method of analysis	Outcome indicator	Main result
Abdel-Aty and Radwan, 2000 United States	1,606 crashes were available at 566 highway segments of State Road 50 in Florida (US). Specific road user groups (i.e. by age and gender) were also investigated.	Negative binomial model	Crash frequency (number of crashes) and Crash involvement frequency	Reduced median width increases the frequency of crashes. Effects are more pronounced for older and female drivers.
Anastasopoulos et al., 2012 United States	Crash data from multilane divided highways in Washington over a 5-year period (9,749 individual crashes resulted in no injury, 3,415 in possible injury, and 3,771 in injury) occurred on 274 homogeneus road sections.	Multivariate tobit model of crash injury-severity rates	Crash rates categorized by injury severities (No injury crash rate, Possible injury crash rate, Injury crash rate)	Narrow medians (less than 40 ft) tend to have a positive effect on no-injury crash rate.
Chimba et al., 2010 United States	4,528 crashes involving a bus at 1,285 uniform segments in Florida (USA).	Negative binomial model and Multinomial logit (MNL) model	Crash frequency (number of crashes) and Injury seveity	Bus crashes rate decreases as median width increases. No significant effect found on crash severity.
Jiang et al., 2013 United States	121,525 total crashes that occurred on 851 state routes (93,783 homogeneous segments) in Tennessee (USA).	One random effect Negative binomial model	Crash frequency (number of crashes)	Lower median widths correspond to higher crash frequencies
Lee and Mannering, 2002, United States	The database contains 120 road sections of highway in Washington State (US) where 489 run-off-the-road crashes occurred during 1994-1996. The paper does not specify the number of rural road sections considered in the study (however according to some calculation they should be 76, with 241 run-off-road crashes.)	Two types of models were developed: a negative binomial model of crash frequency and a nested logit model of crash severity.	Run-off-roadway crash frequency; Possible injury probability; Crash severity probability	Increasing median width was found to reduce the likelihood of run-off-roadway crash occurrence

2.3 RESULTS

Most of the studies indentified that narrow medians appears to have negative effects on road safety.

The effects identified can be summarized as follows:

- 3 studies (Abdel-Aty and Radwan, 2000; Jiang et al., 2013) show a significant increase in the number of crashes, the lower median width the higher the risk of road crashes. Abdel-Aty and Radwan (2000) concluded also that female drivers experience higher probability of crashes than male drivers with reduced median width. Older age drivers have greater tendency to crash occurrence than middle and young drivers when the median is narrow.
- 1 study (Anastasopoulos et al., 2012) shows a significant decrease of no-injury crash rates when medians are narrower than 40 feet (12 m).

- Chimba et al., 2010, studied the effects of median width on frequency and severity of bus crashes. They found a non-significant effect on severity of bus crashes and a significant increase in the number of bus crashes.

A meta-analysis cannot be carried out because a minimum required number of studies (3) has not been achieved, in particular:

a) At least 3 studies did not use the same model form
b) The sampling frames were not similar in all cases

Table 2: Main outcomes of coded studies for narrow median

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects*		Main outcome -description
Abdel-Aty and Radwan, 2000	Median width	Crash frequency	↗	-0,024	The decrease in median width increases crash frequencies
	Median width	Crash involvement frequency / Male	↗	−0,025	The decrease in median width increases crash involvement frequencies for both male and female drivers
	Median width	Crash involvement frequency / Female	↗	-0,063	The decrease in median width increases crash involvement frequencies for both male and female drivers
	Median width	Crash involvement frequency / 15-25 years old	↗	-0,03	The decrease in median width increases crash involvement frequencies for young drivers (15-25)
	Median width	Crash involvement frequency / 26-75 years old	↗	-0,036	The decrease in median width increases crash involvement frequencies formiddle aged drivers (25-75)
	Median width	Crash involvement frequency / >75 years old	↗	-0,094	The decrease in median width increases crash involvement frequencies for older drivers (>75)
Anastasopoulos et al., 2012	Median width less than 40 ft	No injury crash rate	↘	-36,756	If median width is less than 40 ft the number of no injury crash per 100-million VMT is expected to decrease
	Median width less than 40 ft	Possible injury crash rate		-	Non-significant effect on road safety
	Median width less than 40 ft	Injury crash rate		-	Non-significant effect on road safety
Chimba et al., 2010	Median width	Crash frequency	↗	-0.011	medians were found to reduce probability of bus crashes
	Median width	Non-incapacitated injury severity	-		No significant effect. Not included in the final model

	Median width	Incapacitated injury severity	-		No significant effect. Not included in the final model
Jiang et al., 2013		Crash count / Car-crashes	↗	-0.011 (−0.016, −0.007)	Lower median widths correspond to higher crash frequencies
Lee and Mannering, 2002, United States	Median width	Crash frequency / run-off-roadway	↗	0,0330	Increasing median width was found to reduce the likelihood of run-off-roadway crash occurrence.

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The search strategy aimed at identifying the best quality and recent studies to estimate the effect of this risk factor. Only recent journal studies (after 1989) in English language in the field of Engineering and Social science were initially considered from the Scopus database (Table 4). Out of 15 potentially eligible studies were found in Scopus.

TRID database were also investigated leading to 10 potentially eligible studies, it was found no overlap with Scopus results.

Table 4 Literature search strategy **(Scopus database)** 25th March 2016

search no.	search terms / operators / combined queries	hits
#1	("road median*" OR "median*" OR "central reservation*" OR "median strip*" OR "neutral ground" OR "central nature strip*") W/2 ("narrow" OR "width" OR "constricted") AND DOCTYPE (ar OR re) AND PUBYEAR > 1989 AND SRCTYPE (j) AND LANGUAGE (english) AND SUBJAREA (engi OR soci)	101
#2	(((road OR traffic) W/1 ("crash*" OR "accident*" OR "collision*" OR "incident*") W/3 ("probability" OR "risk" OR "odd*")) AND ("road" OR "traffic") AND DOCTYPE (ar OR re) AND PUBYEAR > 1989 AND SRCTYPE (j) AND LANGUAGE (english) AND SUBJAREA (engi OR soci))	2992
#5	#1 AND #2	**15**

Table 5 Literature search strategy **(TRID database)** 25th March 2016

search no.	search terms / operators / combined queries	hits
#1	"narrow median"	**10**

However, after a full-text screening only 4 was coded and included in the synopsis. The following elimination criteria were applied:
Included in meta-analysis
Before-After studies with median evaluated as a safety measure
Results are not based on crashes
Not peer-reviewed
The final 4 studies included in the synopsis indicate that the topic has not been thoroughly investigated.

1 additional relevant study was identified after screening studies from "Safety barriers and obstacles" risk factor. No "grey" literature was examined. No meta-analyses were found.

4 References

A detailed list of studies considered is listed below:

Abdel-Aty M.A., Radwan A.E., (2000). Modeling traffic accident occurrence and involvement. Accident Analysis and Prevention Voume 32, Pages 633–642

Anastasopoulos P.C., Shankar V.N., Haddock J.E., Mannering F.L. (2012). A multivariate tobit analysis of highway accident-injury-severity rates . Accident Analysis and Prevention Volume 45, Pages 110–119

Chimba D., Sando T., Kwigizile V. (2010). Effect of bus size and operation to crash occurrences. Accident Analysis and Prevention Volume 42, Issue 6, Pages 2063–2067

Jiang X., Huang B., Zaretzki R.L., Richards S., Yan X. (2013). Estimating safety effects of pavement management factors utilizing Bayesian random effect models. Traffic injury prevention; 14(7):766-75.

Lee, J. and F. Mannering (2002). Impact of roadside features on the frequency and severity of run-off-roadway accidents: an empirical analysis. Accident Analysis and Prevention 34 149–161

Additional References

Harkey, DL, Srinivasan, R, Baek, J, Council, FM, Eccles, K, Lefler, N, Gross, F, Persaud, B, Lyon, C, Hauer, E & Bonneson, JA (2008), Accident modification factors for traffic engineering and ITS improvements, NCHRP report no. 617, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, USA.

Synopsis 24: Shoulder and roadside deficiencies -Absence of paved shoulders

1 Summary

Charles Goldenbeld & Govert Schermers, & Jan-Hendrik van Petegem, September 27th 2016

1.1 COLOUR CODE: RED

The absence of (paved) shoulders increases the risk of run-of-road crashes on rural highways. Paved shoulders are likely to reduce total crashes or shoulder-related crashes, but at the same time may increase fatal crashes, suggesting that possible speed increase by paved shoulders may counteract its safety effect. The effectiveness of shoulders in reducing crashes depends upon the interaction with other characteristics of the roadway, specifically the number of lanes lane widths and traffic volume.

1.2 KEYWORDS

hard shoulder, soft shoulder, hard strip, paved shoulder, unpaved shoulder, no shoulder, absence of shoulder, crashes

1.3 ABSTRACT

A road shoulder is the section of a roadway that lies immediately adjacent to the travelled lane (or driven carriageway). The absence of a paved shoulder has been identified as a risk factor in studies on 2-lane rural highways. Paved shoulders may increase safety by providing a recovery area for drivers who have left the travelled lane and a place for a driver to maneuver to avoid crashes. However, shoulders may increase crash risk by conflicts caused by vehicles stopped on the shoulder and by inviting higher speeds. Most studies showed that the absence of paved shoulder was associated with an increase in crashes. One study showed that although the presence of shoulders was associated with decreases in injury and property damage crashes, it was also associated with increases in fatal crashes. Another study showed that the presence of paved shoulders was associated with larger safety effects than the presence of unpaved shoulders. In general, the evidence suggests that paved shoulders reduce total and shoulder-related crashes, but the possible speed enhancing effect of (wide) paved shoulders may increase fatal crashes.

1.4 BACKGROUND

1.4.1 Definitions of shoulders

A road shoulder is defined as the section of a roadway that lies immediately adjacent to the carriageway (Labi, 2006). Figure 1 presents an illustration of shoulder as part of the roadway and road environment.

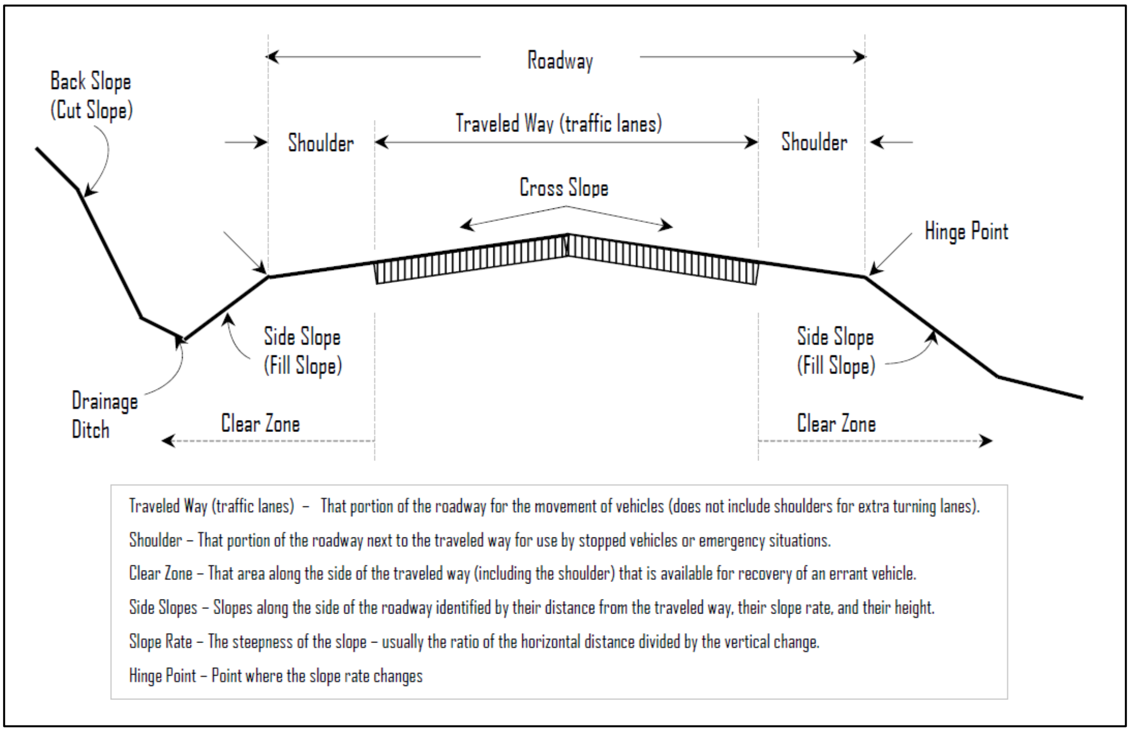

Figure 1. *Roadway cross sectional elements, based on FHWA 1986 reported in Labi (2006).*

1.4.2 Which safety outcomes are affected by shoulders?

The effects of shoulders on road safety has been studied in terms of a number of safety outcomes but predominantly in terms of crash frequency (number of crashes) and less so in terms of injury outcomes (number of injured persons). The most used outcome measures were total crashes or a subgroup of shoulder-related crashes.

1.4.3 How is the effect of shoulders on crashes studied?

Nearly all studies investigated the effect of presence shoulders and shoulder width by developing Accident Prediction Models (APMs) through the application of Generalised Linear modelling (GLM) statistical techniques. Also most of the studies investigated the relationship between the number of crashes (outcome variable) and any number of road design and other features (the independent or predictor variables) and take the form of Poisson or Negative binomial (NB) models.

This synopsis focusses on studies conducted between 1995 and 2016. The coded studies were limited to the USA since these were the studies with the best data and methodology. A few European studies on shoulders have been published (reported in RISER, 2006), but these were often published in Danish, French, German or some other language and many concerned motorways.

1.5 OVERVIEW OF RESULTS

A total of 12 studies were selected as candidate studies for coding. Of these only 5 were found to be suitable and provided sufficient methodological detail allowing the effects to be coded. The 5 studies differed in terms of outcome variables, the analysis period (period of time over which crash data were recorded), the variables included in the model, and statistical modelling procedures. Meta-analysis of these results was therefore not sensible nor advised.

The results can be briefly summarised as follows:

- 5 USA-studies were coded on shoulders, 2 of which related risk to traffic volume, 2 of which related risk to shoulder width, and 1 contrasted paved vs. unpaved shoulders;
- 3 studies showed that the absence of paved shoulder was associated with an increase in crashes (Zegeer and Council, 1995; Harwood et al., 2000; Abdel-Rahim & Sonnen, 2012)
- 1 study showed that prensence of paved shoulders was associated with larger safety effects than presence of unpaved shoulders (Hallmark et al., 2013)
- 1 study indicated that though presence of shoulders was associated with decrease of injury and property damage crashes, it was also associated with increase in fatal crashes (Bamzai et al., 2011).

The results of 4 of the 5 selected studies were consistent in showing that absence of (paved) shoulders on 2 lane rural higways is associated with an increase in total crashes (or shoulder-related crashes). However, in contrast to these positive findings, one recent study indicated that the presence of shoulders may increase fatal crashes while at the same time reducing injury and property damage only crashes (Bamzai et al., 2011). In general, studies indicate that paved shoulders reduce total and shoulder-related crashes, but under some conditions wide paved shoulders may increase fatal crashes, likely through their speed enhancing effect.

1.6 NOTES ON ANALYSIS METHODS

The effect of shoulders on rural 2-lane roads has been mostly studied in USA. Some studies have also been done in Europe, but these are not in English language or not concerned with rural highways.The studies that have been undertaken are generally based on statistical regression models using different sets of dependent and independent variables producing findings that are difficult to compare. As most authors mention, results are study-specific or state-specific limiting transferability of the results to other states or countries. The effect of absence of shoulders has not been systematically studied under varying conditions, for all road user groups and all crash and injury types.

2 Scientific overview

2.1 LITERATURE STUDY

Shoulders placed adjacent to travel lanes serve a number of functions including emergency stopping and pull off areas, recovery area for driver error, and pavement edge support (Stamatiadis et al., 2009). Paved shoulders also allow drainage of water away from the trafficked section of the roadway, increase the effective width of the traffic lanes, and therefore increases the lateral clearances between opposing vehicles on an undivided road (Ogden, 1996). Also, the shoulder may be used to provide a space for very slow vehicles to allow faster vehicles to overtake, and allows moving vehicles to overtake vehicles disabled in the traffic lane (Ogden, 1996).

The use of shoulders by stopped vehicles (e.g. in the case of a breakdown or similar) may pose a hazard. Past research has shown that 11% of fatal freeway crashes are related to vehicles stopped on shoulders (Stamatiadis et al., 2009). The same review also presents evidence that wider shoulders may encourage higher operating speeds because they may communicate to the driver the presence of wider space for correcting errors (Stamatiadis et al., 2009).

In general shoulders are part of the carriageway and their effectiveness depends upon other characteristics of the roadway. Specifically, the number of lanes, lane width, and shoulder width are all interrelated, and the dimensions of any of these elements typically has an effect on the other elements (Stamatiadis et al., 2009; iRap, 2013). Also the possible use of shoulders by vulnerable road users may play a role in safety effects (iRap, 2013).

Reviewing American studies on safety effect of shoulders, Bamzai et al. (2011) observe the following:

- Concerning multilane highways there is mixed evidence for safety effects of wide shoulders, with several studies showing safety effects but others showing the opposite: more crashes on sections with wide shoulders.
- On rural multi-lane highways, the optimal shoulder widths would be 6-9ft. In one study it was found that using a 6-ft shoulder width decreased crash rate by 16 percent.
- Concerning 2-lane rural highways the evidence indicates that safety effects of presence of paved shoulders depend upon factors such as lane width, shoulder width, and traffic volume. In general, the larger the lane width, the smaller the required shoulder width can be to reduce crashes. For 2 lane rural highways with high traffic volumes the difference in crash rate between highways paved and unpaved shoulders may decrease.
- In one large scale study on 2 lane rural higways widening of shoulder widths from no shoulder to 1-3ft, to 4- 6 6ft, and to 7-9ft was found to reduce related crashes by 6 percent, 15 percent, and 21 percent, respectively.

In their (brief) review of paved shoulders Hallmark et al (2013) conclude the following:

- Addition of paved shoulders is especially effective in reducing run-of-road crashes
- In general roads, and specifically 2 lane rural highways, with paved shoulders have lower crash rates than roads (highways) with unpaved shoulders of the same width.
- Most but not all studies indicate that paved shoulders offer a significant safety benefit for 2 lane rural highways.

- Whether shoulders were paved or unpaved and shoulder width had a greater effect on crash rates than lane width. Wider shoulders tend to have fewer crashes on rural two-lane highways.

At the European level, several EU-research projects have been concerned with safe road shoulders:
– RISER ("Roadside Infrastructure for Safer Roads") was a European project that aimed at the identification of danger zones, drawing up guidelines, carrying out inspections and giving trainings (RISER, 2006).
– EuroRAP ("European Road Assessment Programme") is a programme which gives roads (including the road shoulder) a safety score (EuroRAP, 2009).
– SafetyNet offers Safety Performance Indicators for roads and road shoulders (Hakkert et al., 2007).
– FEMA (Federation of European Motorcyclists' Associations) is dedicated to motorcycle-friendly safety barriers at European level (FEMA, 2005).

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 What is the relationship between crashes and shoulders

5 studies were selected for coding on the basis of providing information on safety effects of presence versus absence of paved shoulders. The focus was on studies between 1995-2016, but one study was included that analysed data before that period (Zegeer & Council, 1995). Although this study uses data from the 1980s, the study outcomes still merit attention in view of the size of its database and the studied interactions between lane width and road width.

The 5 studies all concerned safety effects of shoulders versus no shoulders on 2 lane rural highways in the USA. The 5 studies differed in several respects. Some studies analysed total crashes (Abdel-Rahim & Sonnen, 2012; Hallmark et al., 2013) whereas others analysed subgroups of crashes (Harwood et al., 2000; Bamzai et al, 2011; Zegeer & Council, 1995). One study analyses crashes according to injury injury levels (Bamzai et al., 2011), but 4 others used no injury distinction. All 5 studies used unique different databases, with different lengths of accident periods, and all studies used unique analysis models.

Two studies related safety of shoulders to traffic volume (Harwoord et al., 2000; Abdel-Rahim & Sonnen, 2012), two studies related safety of shoulders to shoulder width (Bamzai et al., 2011, Zegeer and Council, 1995), and one study specifically compared paved verus unpaved shoulders (Hallmark et al., 2013).

Zegeer and Council (1995) found that paved shoulders with widths of 2, 4, 6 and 8 ft. (versus no shoulders at all) were associated with percentage accident reductions of 43%, 52%, 59%, 65% when lanes were widened with 3ft, with 35%, 45%, 53%, 61% when lanes were widened by 2 feet, and with 26, 37, 47, 55% when lanes were widened by 1 foot (1 feet = 0.3048 m). According to Zegeer and Council, one foot increase shoulder width yields about 8 and 7% decrease in accident rate on paved and unpaved shoulders respectively.

For rural two-lane highways with 500, 1000, 1500, 2000, 2500 vehicles/day (ADT), Harwood et al. (2000) estimated the crash modification factors for no shoulder versus a standard 6 foot shoulder to be 1.10, 1.24, 1.35, 1.50 and 1.50. Their results revealed that a road without paved shoulders will have between 10 and 50% more crashes atADT levels of between 500-2500 vehicles/day when compared to a road with a standard 1,8m paved shoulders.

Abdel-Rahim & Sonnen (2012) found the following safety effects for absence of shoulder on 2-lane rural highways:
- The Crash Modification Factors for rural 2-lane highways with no/very narrow shoulders (< 1 ft or 33cm) were 1.16 for all crashes, 1.17 for single-vehicle crashes, and 1.15 for multiple-vehicle crashes. This corresponds to an average increase in crashes of 16 percent when compared to highways with a 3 ft (0,9m) wide shoulder. This estimate has been corrected for possible differences in traffic volume which was one of the predictors in the statistical model
- For low-volume highways, the average increase in crashes for highways with no shoulders was at 13 percent when compared to highways with a 3 ft shoulder width (CMFs 1.13, 1.14, 1.11 for all crashes, single vehicle crashes and multiple vehicle crashes).

Hallmark et. al. (2013) estimated the expected change in total crashes for paved versus unpaved shoulders to be 8.8% after one year (the 95% CI for the ratio is [0.050, 0.124] indicating an expected reduction in crashes between 5.0% and 12.4% after one year).

In contrast to previous positive findings, Bamzai et al. (2011) found that adding paved 6 ft or 8 ft shoulders on 2-lane rural highways led to increases in fatal shoulder-related crashes (6ft/8ft: -8/-11% reduction), but decreases in injury (5%/8% reduction) and Property Damage Only crashes (25%/43% reduction).

The effects of (paved) shoulders (vs. no shoulders) on 2-lane rural highways can thus be summarised as follows:

- 3 studies with significant accident reductions for shoulders vs. no shoulders
- 1 study indicating larger crash reductions for paved shoulders compared to unpaved shoulders
- 2 studies indicating larger crash reductions on rural higways with higher traffic volumes
- 2 studies indicating larger crash reductions with wider shoulders
- 1 study indicating larger crash reductions for paved shoulders compared to unpaved shoulders
- In contrast to positive findings: 1 study with significant increase in fatal crashes and decreases in injury and PDO crashes

Overall (based on all crashes) the studies seem to suggest that absence of (paved) shoulder on 2-lane rural highways leads to an increase in the number of crashes. However, speed enhancing effects of (broad) shoulders may counteract safety improvement.

Table 1 summarises the main findings.

Table 1 Main study outcomes

Author, yr.		Simplified summary of main outcomes
Zegeer & Council 1995	↑	Paved shoulders of 2,4,6,8 ft. (versus no shoulders) at all were associated with percentage accident reductions of 43, 52, 59, 65% when lanes were widened with 3ft., with 35, 45, 53, 61 % when lanes were widened with 2 ft., and with 26, 37, 47, 55% when lanes were widened with 1 ft.
Harwood 2000	↑	For rural two-lane highways with 500, 1000, 1500, 2000, 2500 vehicles/day (ADT), the crash modification factors for no shoulder vs. standard 6 ft. shoulder were 1.10, 1.24, 1.35, 1.50 and 1.50.
Bamzai 2011	↑↓	For 2-lane rural highways, adding paved 6 ft or 8 ft shoulders led to increases in fatal shoulder-related crashes (6ft/8ft: -8/-11% reduction) but decreases in injury (5%/8% reduction) and PDO crashes (25%/43% reduction).
Abdel-Rahim 2012	↑	The Crash Modification Factors for rural 2-lane highways with no/very small shoulders (< 1 ft) were 1.16, 1.17, and 1.15 for all crashes, single-vehicle crashes, and multiple-vehicle crashes, respectively. For low-volume highways, the CMFs were 1.13, 1.14, 1.11 for all crashes, single vehicle crashes and multiple vehicle crashes, respectively.

Hallmark 2013	↑	The expected change in total crashes for paved vs. unpaved shoulders was 8.8% after one year (the 95% CI for the ratio is [0.050, 0.124] indicating an expected reduction in crashes be-tween 5.0% and 12.4% after one year).

2.3 ANALYSIS METHODS

2.3.1 Introduction

The estimates in the 5 coded studies were subject to different statistical models with different sets of dependent and independent variables and therefore the estimates are not directly comparable. Therefore the results do not lend themselves for meta-analysis. Below we describe the methods of coded studies.

Although the results by Zegeer and Council (1995) are based on data from the 1980s, the study outcomes still merit attention in view of the size of its database and the studied interactions between lane width and road width. An accident prediction model was developed for two-lane, rural roads and used to determine the expected effects of lane- and shoulder widening improvements on related accidents. The model was based on analysis of data for nearly 8 050 km (5,000 miles) of two-lane highway from seven states. The studied accident types included run-off-road (fixed object, rollover, and other run-off-road accidents), head-on, and opposite- and same direction sideswipe accidents, which together were termed as "related accidents. In this study, the information on crash relationships for lanes, shoulders, and bridges (and corresponding effectiveness information for countermeasures) were for two-lane, rural roads. The predictive model applied to two-lane, rural roadways with lane widths of 8 to 12 ft (2.4 to 3.7 m), shoulder widths of zero to 12 ft (3.7 m) (paved or unpaved), and traffic volumes of 100 to 10,000.
Harwood et al. (2000) used an approach to crash prediction on 2 lane rural highways in Minnesota and Washington that combined the use of historical crash data, regression analysis, before-and-after studies, and expert judgment to make safety predictions. An expert panel met and used the findings of the literature review as the basis for (1) selecting the final set of geometric and traffic control elements for which Crash Modification Factor (CMFs) could be developed; and (2) quantifying those CMFs. For roadway segments, the final CMFs included all of the variables in the roadway segment base models plus additional variables.

Using a 6-foot-wide (1,8m) paved shoulder as a base value, the authors determined the crash modification factor (CMF) of roads with no paved shoulder and under different traffic volumes. A CMF greater than 1.0 would indicate that more crashes were expected on roads without shoulders whne compared to a standard 6-foot (1,8m) shoulder. The crash modification factors for absence of shoulders concerned the following group of crashes: single vehicle run of road accidents, multiple vehicle same direction sideswipe accidents, and multiple-vehicle opposite direction accidents.

Abdel-Rahim & Sonnen (2012) examined the relationship between crash rates and shoulder width and lane width for two-lane rural state highways in Idaho. Crash modification factors (CMFs) for shoulder width and lane width were developed using Idaho crash data covering the period from 1993 to 2010. Generalised linear negative binomial models were used to develop prediction models for assessing the safety impacts of using different lane width and shoulder width values. Models were developed for all crashes, single-vehicle crashes and multiple-vehicle crashes.Models for specific crash types such as run-off-road (ROR), opposite direction (OD), single vehicle, and/or sideswipe crashes were not developed due to the limited number of crashes and the small sample size available. The model coefficients were estimated using the maximum-likelihood method.

A total of 127 roadways segments from 48 different highways in Idaho with lengths ranging from 5 to 8 miles (8,0 – 12,8km)were selected for the analysis. The total length of the roadway segments included in this study is 923 miles (1477km) of rural two-lane two-way state highways. A total of 7,977 crashes occurred on these segments covering the years from 1993 through 2010. GLMs were used in the development of the prediction models in this study. The Generalised Modeling procedure (GENMOD) in SAS statistical software was used to develop the prediction models. The model coefficients were estimated using the maximum-likelihood method. In addition to the general analyses, crash modification factors were also separately calculated for low volume 2 lane rural highways. Low-volume highways were defined as highways with an Average Annual Daily Traffic (AADT) of less than 400 vehicles per day.

Hallmark et. al. (2013) evaluated the effectiveness of paved shoulders in reducing crashes in Iowa. Data, such as shoulder type and width, pavement type, presence of rumble strips, and lane width, were collected for non-interstate rural roadways where paved shoulders had been installed. Data on 220 road segments were collected, amongst which 170 2-lane and 54 4-lane sections.

The researchers used a negative binomial-Lindley (NB-L) generalised linear model (GLM). This model was specically chosen to overcome the well-known problematic distribution of crash data, namely thatcrash data sets often contain a large amount of zeros and a long or heavy tail (which creates highly dispersed data). For such datasets, the number of zero crash sites is so large that traditional distributions and regression models, such as the Poisson and Poisson-gamma or negative binomial (NB) models cannot be used efficiently. To overcome this problem, the NB-Lindley (NB-L) distribution has been introduced for analysing count data that are characterized by excess zeros. According to Lord & Geedipally (2011) this new distribution can provide a better statistical fit than the traditional Negative Binomial for datasets that contain a large amount of zeros. Since this distribution is also influenced by the length of the tail, these authors suggest to evaluate both the NB and NB–L distributions and select the one that provides the best goodness-of-fit statistic.

The model included the following road characteristics variables: Paved vs. unpaved shoulder, speed limit, median type, season, length of segment, presence or absence of rumble strips, total width of right shoulder, total width of right paved shoulder, total width of unpaved shoulder, number of lanes.

The one evaluation study with mixed safety results was perfomed by Bamzai et al. (2011). These researchers used an Empirical Bayesian (EB) approach to perform before-after comparison of vehicle crashes on a number of rural and urban Interstate, multilane, and two-lane highway segments involving pavement resurfacing treatments (with and without shoulder paving). Data on Illinois state-maintained highways for the period 2000-2006 were used.

Table 2 summarises the main features of coded studies (sample, method, outcome indicator).

Table 2 Description of coded studies

Author, Year	Sample and study design	Method of analysis	Outcome indicator
Zegeer & Council 1995	Analysis of data for nearly 8 050 km (5,000 miles) of two-lane highway from seven states.	Accident prediction model using lognormal regression	Analysed crash group included run-off-road (fixed object, roll-over, and other run-off-road crashes), head-on, and oppo-site- and same direc-tion sideswipe crashes.
Harwood 2000	Data from 619 rural two- lane highway segments in Minnesota and 712 road-way segments in Wash-ington. The segments included approx. 1,130 km (700 mi) roadways in Minnesota and 850 km (530 mi) in Washington.	Negative binomial regres-sion analysis on 5 years of accident data (1985-1989) for each roadway segment in Minnesota and 3 years of accident data (1993-1995) for each roadway segment in Washington.	Analysed group of crashes included: single vehicle run of road crashes, mul-tiple vehicle same direction sideswipe crashes, and ultiple-vehicle opposite direction crashes.
Bamzai 2011	Before-after comparison of vehicle crashes on a number of rural and urban Interstate, multilane, and two-lane highway seg-ments involving pavement resurfacing treatments (with and without shoulder paving).	Data on Illinois state-maintained highways for the period 2000-2006 were used. Empirical Bayesian (EB) approach in combination with cross-sectional analysis.	Separate estimates for shoulder-related fatal crashes, shoulder-related injury crashes and shoulder-related property damage only crashes
Abdel-Rahim 2012	A total of 127 roadways segments from 48 high-ways in Idaho with lengths 5 to 8 miles were selected for analysis. The total length of the roadway segments included was 923 miles of rural two-lane two-way state highways. A total of 7,977 crashes occurred on these seg-ments from 1993 through 2010.	A generalized modeling procedure (GENMOD/SAS) was used to develop the prediction models (with maxi-mum-likelihood estimation of model coef-ficients). Crash modification factors were separately calculated for low volume 2 lane rural highways (de-fined as high-ways with an Average An-nual Daily Traf-fic < 400 vehicles per day).	Separate estimates for all crashes, single vehicle crashes, and multiple-vehicle crashes.
Hallmark 2013	Data on 220 road segments in Iowa were collected, amongst which 170 2-lane and 54 4-lane sections.	A negative binomial-Lindley (NB-L) generalized linear model (GLM) was used in-cluding: Paved vs. unpaved shoulder, Speed limit, Median type, season, length of seg-ment, presence/ ab-sence rumble strips, right shoul-der width, right paved shoulder width, unpaved shoulder width, nr. lanes.	Total crashes

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature on shoulders and road safety was searched for in the international databases Scopus and TRID on 27 March 2016. Scopus is the largest international peer-reviewed database indexing scientific journals, books and conference proceedings from more than 5,000 publishers. TRID is an integrated database that combines the records from TRB's Transportation Research Information Services (TRIS) Database and the OECD's Joint Transport Research Centre's International Transport Research Documentation (ITRD) Database. TRID provides access to more than one million records of transportation research worldwide.

For Scopus the following query was used to select papers about road safety (Table 1): ((road and casualt*) or (road and injur*) or (road and accident*) or (road and crash*) or (traffic and injur*) or (traffic and casualt*) or (traffic and accident*) or (traffic and crash*)). For TRID the following query was used: (collision* or crash* or accident* or injur* or casualt*) AND (traffic or road). Both for Scopus and TRID all search results were filtered on English language only.

The aforementioned queries were combined with a query to select papers relating to the risk factor absence of shoulder (Table 1): ("hard shoulder" OR "soft shoulder" OR "hard strip" OR "paved shoulder" OR "unpaved shoulder" OR "no shoulder" OR "missing shoulder" or "absent shoulder" or "absence of shoulder" or "shoulder is missing" or "shoulder is absent" or "absence of shoulder") AND NOT TITLE-ABS-EY (fracture OR trauma OR tissue OR disorder* OR surgery)).

These queries were combined in Scopus and TRID to search for literature about the risk factor absence of shoulders. Searches were done for Worldwide and Europe. To distinguish literature from Europe and Worldwide, the results were loaded into Mendeley, where the following query was used to identify literature from Europe: (Italy or Ireland or Hungary or Greece or Germany or France or Finland or Estonia or Denmark or Czech or Cyprus or Croatia or Bulgaria or Belgium or Austria or Scotland or England or Britain or United Kingdom or Sweden or Spain or Slovenia or Slovakia or Romania or Portugal or Poland or Netherlands or Malta or Luxembourg or Lithuania or Latvia).

Database: Scopus/TRID Date: 27 March 2016

	Search terms/logical operators/combined queries
1	Scopus: ((road and casualt*) or (road and injur*) or (road and accident*) or (road and crash*) or (traffic and injur*) or (traffic and casualt*) or (traffic and accident*) or (traffic and crash*)) TRID: (collision* or crash* or accident* or injur* or casualt*) AND (traffic or road).
2	("hard shoulder" OR "soft shoulder" OR "hard strip" OR "paved shoulder" OR "unpaved shoulder" OR "no shoulder" OR "missing shoulder" or "absent shoulder" or "absence of shoulder" or "shoulder is missing" or "shoulder is absent" or "absence of shoulder") AND NOT TITLE-ABS-EY (fracture OR trauma OR tissue OR disorder* OR surgery)).

Table 1: Used search terms and logical operators

The number of hits for Europe and Worldwide and for Scopus and TRID are presented in table 2.

search no.	Region	Database	hits
#1	Europe	Scopus	24
#2	Europe	TRID	90
#3	Worldwide	Scopus	64
#4	Worldwide	TRID	218

Table 2: *Number of hits per search*

Following the initial selection of relevant publications, a new selection of publications was made in Mendeley, sorting the publications on year and source. Only publications from trusted sources and most recent publications were selected with a maximum number of about 80. From this selection all abstracts were reviewed. From reviewing the abstracts a total of 18 publications were selected as the most promising. For 6 of these the full text version could not be retrieved and these were not considered further. The remaining 12 publications were reviewed and 5 of these were judged suitable for coding.

The final studies selected for the topic shoulders suggest that although this topic has been studied in some depth, the study methodologies and subsequent results are diverse and mixed. No meta-anlyses were found on this topic and the literature review reveals that the results of the selected five studies do not lend themselves for inclusion in a meta-analysis.

3.2 LIST OF STUDIES

A list of studies considered (and of which the first 5 were selected for coding) are listed below:

3.2.1 Coded studies

1. Abdel-Rahim, A. & Sonnen, J. (2012). *Potential safety effects of lane width and shoulder width on two-lane rural state highways in Idaho*. Idaho: National Institute for Advanced Transportation Technology. Idaho, USA

2. Bamzai, R., Lee, Y., & Li, Z. (2011). *Safety impacts of highways shoulder attributes in Illinois*. Illinois: Illinois Center for Transportation.

3. Hallmark, S.L., Qiu, Y., Pawlovitch, M. & McDonald, T.J. (2013). Assessing the safety impacts of paved shoulders. *Journal of Transportation Safety & Security*, *5*, 131-147.

4. Harwood, D.W., Council, F.M., Hauer,. E., Hughes, W.E., & Vogt, A. (2000). *Prediction of the expected safety performance of rural two-lane highways*. Washington: Federal Highway Administration, Midwest Research Institute.

5. Zegeer, C.V. & Council, F.M. (1995). Safety relationships associated with cross-sectional roadway elements. *Transportation Research Record*, *1512*, 29-36,

3.2.2 Not coded considered studies

6. Akgüngör ,A.P., Yildiz, O. (2007). Sensitivity analysis of an accident prediction model by the fractional factorial method. *Accident Analysis & Prevention*, *39*, 63-68.

7. Aram, A., Nilam, M., Condo, T.A. & Ampang, J. (2010). Effective safety factors on horizontal curves of two-lane highways. *Journal of Applied Sciences*, *10*, 2814-2822. .

8. Elefteriadou, L., Torbic, D., El-Gindy, M., Stoffels, S. & Adolini, M (2001). *Rumble strips for roads with narrow or non-existent shoulders*. Pennsylvania: Pennsylvania Transportation Institute. USA, Pennsylvania

9. Hallmark, S.L., McDonald, T.J., Tian, Y., Andersen, D.J. (2009). *Safety benefits of paved shoulders*. Iowa: Center for Transportation Research and Education. USA, Iowa

10. Lynam, D.A. & Kennedy, J.V. (2005). *The travel of errant vehicles after leaving the carriageway*. PPR298. Crowthorne: TRL Limited UK

11. Shahrom, M., Saman, B.A., Umar, R., & Sohadi, B.R. (2004). The effectiveness of a continuous paved shoulder to reduce motorcycle accidents at junctions. Paper presented at: Malaysian Road Conference, 6th, 2004, Kuala Lumpur, alaysia. REAAA Journal, 2005, (Road Engineering Association of Asia & Australasia). Malaysia

12. Summersgill, I., Kenedy, J.V., Sharples, J.M., & Frew, M.J. (2004). *Safety on hard shoulders on dual two-lane and three-lane motorways*. PPR017. UK, Crowthorne: TRL Limited. UK

3.2.3 References on general background

iRap (2013). Road Attribute Risk Factors: Paved Shoulder Width. Factsheet, iRap, May 2013.UK, Hampshire: iRap.

EuroRAP (2009). Star Rating Roads For Safety, The EuroRAP Methodology. EuroRAP505.04_v2 090911. EuroRAP AISBL.

FEMA (2005). The Road to Success – Improving Motorcyclists' Safety by Improving Crash Barriers. Federation of European Motorcyclists' Associations

Hakkert, A.S, Gitelman, V. and Vis, M.A. (Eds.) (2007) Road Safety Performance Indicators: Theory. Deliverable D3.6 of the EU FP6 project SafetyNet.

Labi, S. (2006). *Effects of geometric characteristics of rural two-lane roads on safety. Report No. FHWA/IN/JTRP-2005/2*. Indiana, West Lafayette: Purdue University.

Lord, D. & Geedipally,S.R. (2011). The negative binomial–Lindley distribution as a tool for analyzing crash data characterized by a large amount of zeros. *Accident Analysis and Prevention*, *43*, 1738-1742.

Ogden, K.W. (1996). The effects of paved shoulders on accidents on rural highways. *Accident. Analysis and Prevention*, *29*, 353-362.

RISER (2006). *D06: European Best Practice for Roadside Design: Guidelines for Roadside Infrastructure on New and Existing Roads*. RISER deliverable, February 2006. Gothenburg: Chalmers University of Technology/RISER.

Stamatiadis, N., Pigman, J., Sacksteder, J., Ruff, W., & Lord, D. (2009*). Impact of shoulder width and median width on safety*. NCHRP Repprt 633. Washington D.C.: Transportation Research Board.

Synopsis 25: Shoulder and roadside deficiencies - Narrow shoulders

1 Summary

B. Loenis, G. Schermers, J.W.H. van Petegem (SWOV, sept. 2016)

1.1 COLOUR CODE: RED

Narrow(er) shoulders increases the risk of run-off-road crashes on 2 lane rural highways. In general, wider shoulders are associated to lower crash rates. The effect of shoulder width in reducing crashes depends upon its interaction with other characteristics of the roadway, specifically, number of lanes and lane widths.

1.2 KEYWORDS

Narrow shoulders, shoulder width, crash prediction model, road safety, highways.

1.3 ABSTRACT

A road shoulder is that section of roadway immediately adjacent to the travelled lane and is generally reserved for use as an emergency lane, on mainland European roads it is located on the right had side of the road. The shoulder can be surfaced or unsurfaced. The lack of adequate shoulder width has been identified as a risk factor in studies on 2-lane rural highways. Paved shoulders may increase safety by providing a recovery area for drivers who have left the travelled lane and they provide a place for a driver to stop a defective vehicle and avoid crashes. However, at the same time, shoulders may to some extent increase the risk of conflicts caused by vehicles stopped on shoulder and by inadvertently inviting higher speeds (wide shoulders and wide lanes lead to a generous cross section). The described effects depend not only on the presence of a road shoulder but also on the width of the road shoulder. A wider road shoulder provides the driver with more recovery area but may trigger higher speeds. Five USA-studies were coded on shoulder width. All five studies showed that wider shoulders were associated with a decrease in crashes. One study also combined the variables shoulder width and the presence of shoulder rumble strips and showed a decrease of the number of crashes. Another study combined the variables shoulder width and speed limit and showed a decrease of crashes for an increase of the shoulder width on roads with a higher speed limit. A third study combined the variables shoulder width and lane width and showed a decrease in the number of crashes. The remaining two studies showed the single effect of shoulder width on the number of crashes. In general, the evidence is conclusive that narrow shoulders increase the number of crashes compared to wider shoulders, be it for different conditions.

1.4 BACKGROUND

1.4.1 How does shoulder width affect road safety?

Shoulders placed adjacent to travel lanes serve a number of functions. These include facilitating emergency stopping and pulling off, provide a recovery area for driver error, and pavement edge support (Stamatiadis et al., 2009). Paved shoulders also allow drainage of water away from the trafficked section of the pavement, and increase the effective width of the carriageway, and therefore increase the lateral clearances between opposing vehicles on an undivided road (Ogden, 1996). Also, the shoulder may be used to provide a space for very slow vehicles to allow faster vehicles to overtake, and allows moving vehicles to overtake vehicles disabled in the traffic lane (Ogden, 1996). However, the use of shoulders to provide an area for a stopped vehicle may pose a hazard since past research has shown that 11% of fatal freeway crashes are related to vehicles stopped on shoulders (Stamatiadis et al., 2009). The same review also presents evidence that wider shoulders may encourage higher operating speeds because they may communicate to the driver the presence of wider space for correcting errors (Stamatiadis et al., 2009).

In general, shoulders are part of the wider roadway and their effectiveness depends upon other characteristics of the roadway. Specifically, the number of lanes, lane width, and shoulder width are all interrelated, and the values for any of these elements typically has an effect on the values of the other elements (eg. a wider lane width might result in a smaller shoulder) (Stamatiadis et al., 2009; iRap, 2013). Also the possible use of shoulders by vulnerable road users may play a role in safety effects (iRap, 2013).

1.4.2 Which safety outcomes are affected by shoulder width?

The effects of narrow shoulders on road safety have been studied in terms of a number of safety outcomes but predominantly in terms of crash frequency (number of crashes) and less so in terms of injury outcomes (number of injured persons). The most used outcome measures were total crashes or a subgroup of shoulder-related crashes.

1.4.3 How is the effect of shoulder width on crashes studied?

Nearly all studies investigated the effect of presence of shoulders and shoulder width as part of Crash Prediction Models (CPMs) developed through the application of Generalized Linear modelling (GLM) statistical techniques. Also most of the studies investigated the relationship between the number of crashes (outcome variable) and a number of road design and other features (the independent or predictor variables) and take the form of Poisson, Bayesian or Negative binomial (NB) models.

This synopsis focusses on studies conducted between 2008 and 2014. The coded studies were limited to the USA since these were the studies with the best data and method.

1.5 OVERVIEW RESULTS

A total of **30** studies were selected as candidate studies for coding. Of these only 5 were found to be suitable and provided sufficient methodological detail allowing the effects to be coded. Because of the fact that the study designs, the applied methods and input data are somewhat heterogeneous and inconsistent, potential transferability of results is unlikely.

The results of all selected studies were consistent in showing that wider shoulders are associated with a decrease in total crashes or that narrow shoulders are associated with an increase of total crashes. In general, the evidence from the selected studies suggests that wider shoulders reduce total crashes.

1.6 NOTES ON ANALYSIS METHODS

The majority of the identified studies on shoulder width have been undertaken in the USA. The studies that have been undertaken are generally based on statistical regression models using different sets of dependent and independent variables producing findings that are difficult to compare. As most authors mention, results are study-specific or state-specific limiting transferability of the results to other states or countries. The effect of narrow shoulders has not been systematically studied under varying conditions, for all road user groups and all crash and injury types.

2 Scientific overview

2.1 LITERATURE REVIEW

2.1.1 Definitions of shoulder width

A road shoulder is defined as the section of a roadway that lies immediately adjacent to the carriageway (Labi, 2006). Figure 1 presents an illustration of shoulder as part of roadway and road environment.

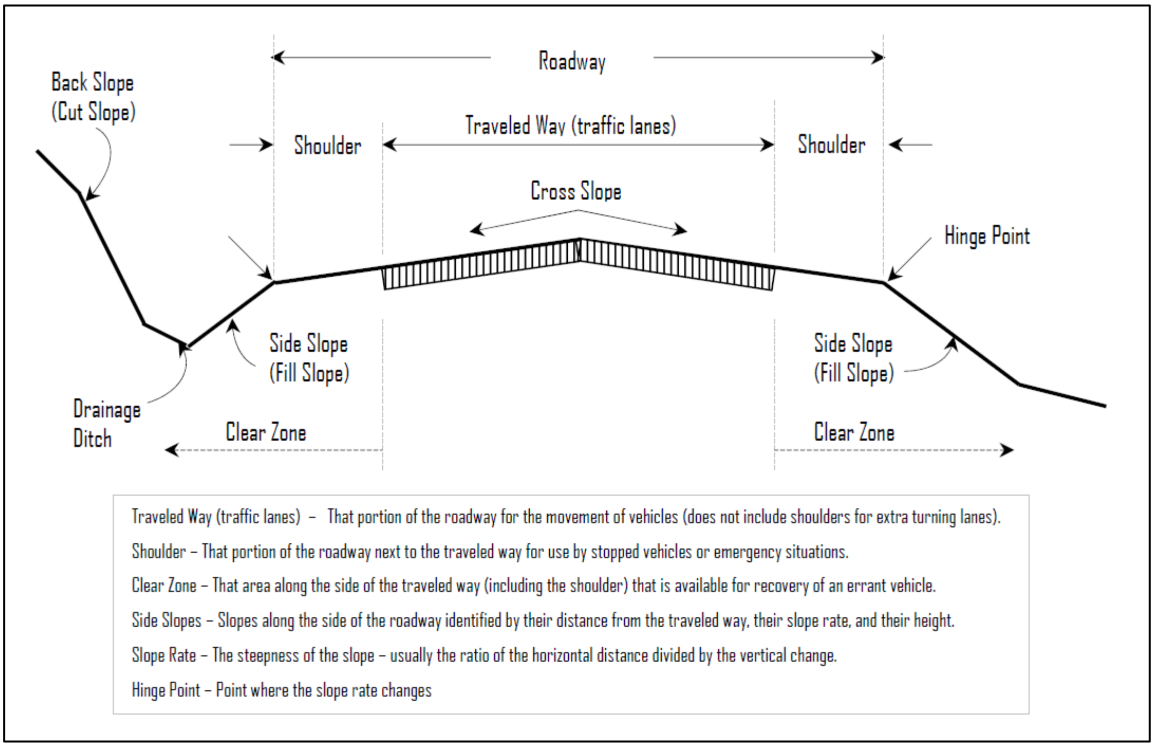

Figure 1: *Roadway cross sectional elements, based on FHWA 1986 reported in Labi (2006).*

2.1.2 Description of coded studies

5 studies were selected for coding on the basis of providing information on safety effects of narrow shoulders. The focus was on studies between 2008-2014. The 5 studies all concerned safety effects of either the widening or narrowing of shoulders with different shoulder widths in the USA. The 5 studies differed in several respects. Two studies analysed total crashes (Gross et al., 2009; Ma et al, 2008) whereas three studies analysed subgroups of crashes (Park et al., 2014; Stamatiadis et al., 2009; Islam et al., 2014). Three studies analyse crashes according to injury levels (Park et al., 2014; Islam et al., 2014; Ma et al., 2008), but two studies did not distinguish between injury types. All 5 studies used different databases, with different lengths of accident periods, and all studies developed CPM's unique to the given set of data and using different (dependent and independent) variables in the models.

Four studies related traffic safety to the width of the shoulder, in which road segments with a narrow shoulder were used as reference and compared to road segments with a wider shoulder. Of these four studies one study included the variable 'speed limit', another study included the variable 'presence of shoulder rumble strips' and the other two only used shoulder width as variable. The fifth study used road segments with a combination of wide shoulder and wide lane and compared them to road segments with narrower and varying shoulder and lane widths.

A paper by Park et al. (2014) explores and compares CMFs for multiple treatments of shoulder width and shoulder rumble strips on rural multilane roadways. The single treatment includes the applying shoulders with different widths and is based on before-after and cross-sectional methods. The interaction treatment includes the widening of shoulders in combination with the presence of shoulder rumble strips and experiments with six methods for the combining of single CMFs. The study distinguishes two crash types (all and single vehicle run-off roadway crashes) and three crash severities (all severities, fatal and injury). The exact widening is not clearly stated in the paper but the effect of the widening is shown. The collected data included the following variables: type of road, number of lanes, section average daily traffic (ADT), median width, median type, shoulder width, shoulder type, maximum speed limit and lane width. For all four categories the CMFs are smaller than one, implying a reduction in total, fatal and injurious crashes for wider shoulders. Based on the CMFs there is a negligible difference between total, fatal an injury crashes. When examining the type of crash, it can be seen that the subgroup single vehicle run-off road shows a larger reduction compared to all crashes. A further distinction was made between the original shoulder widths (before widening). It was found that the widening of shoulders was more safety effective (lower CMFs) for the roadway segments with narrower original shoulder width in the before period, compared to roadway segments with wider original shoulder width.

A paper by Gross et al. (2009) presents an evaluation of shoulder and lane width combinations on rural two-lane undivided roads. In the study a matched case-control analysis is used with a conditional logistic regression to investigate the relationship between outcome and risk factor. Matching is used to control the effects of AADT and segment length whist speed limit, lane width, shoulder width and horizontal and vertical curve presence are included in the model as covariates. . In the study a road segment with a shoulder width of 1,83 m and a lane width of 3,66 m is compared to combinations of equal or narrower widths. In general, the results show that wider lanes and wider shoulders are associated with a reduction in crash risk. For a fixed pavement width (total of lane and shoulder width) the results are not as clear. The results are too mixed to indicate a clear preference for wider shoulders or wider lanes for a fixed pavement width.

A paper by Stamatiadis et al. (2009) presents Negative Binomial (NB) models to evaluate the impact of shoulder width on crashes. Next to shoulder width, the study included road type, median barrier, paved right shoulder, ADT and median width as independent variables. The study distinguished two main road categories, divided and undivided rural roads. For divided rural roads a further distinction was made for single-vehicle crashes, multi-vehicle crashes and all crashes. For undivided rural roads a further distinction was made for multi-vehicle crashes and all crashes. For all categories the reference shoulder width was set at 3 ft (0,9 m). For divided road segments this was the average of left and right shoulder in the same direction. For undivided road segments this is the average of the right shoulder. The reference width is compared with test widths of 0 ft (0 m), 4 ft (1,2 m), 5 ft (1,5 m), 6 ft (1,8 m), 7 ft (2,1 m), 8 ft (2,4 m) and 10 ft (3,0 m). For all categories the results show CMFs > 1 for narrower shoulders (0 ft), implying an increase of crashes and CMFs < 1 for wider lanes, implying a decrease of crashes for wider lanes. The results show that widening a narrow shoulder has more effect than widening a wide shoulder. The comparison of undivided and divided roads shows that the widening of the shoulder has more effect on divided roads, for both multi-vehicle and total crashes. Single-vehicle crashes on divided roads are less affected by shoulder widening, while multi-vehicle crashes are more affected by shoulder widening.

A paper by Islam et al. (2014) developed safety performance functions (SPFs) for freeways by considering interactions between speed limit and geometric variables. With the use of a negative binomial (NB) model, several SPFs were developed for the single variable shoulder width and the combination of the variables shoulder width and speed limit. Besides shoulder width and speed limit other variables are included: AADT, length, median type, number of lanes and several other interactions with speed limit. The study distinguishes two types of crashes: single- and multi-vehicle crashes and two levels of severity: total and fatal and injury crashes. In the study the reference road segment have a shoulder width smaller than 10 ft (3 m) and are compared with road segments which have a shoulder width larger than 10 ft (3 m). No significant results were obtained for any of the crash severities of multi-vehicle crashes. For single-vehicle crashes significant results were obtained for both the single and interaction variables. Both the total number of crashes and the fatal and injury crashes were found to have a negative coefficient, implying a decrease in crashes for shoulder widths larger than 10 ft compared to shoulder widths smaller than 10 ft. The study also investigated the combined effect of shoulder width and speed limit distinguishing speed limits of 50 mph (80,5 km/h), 55 mph (88,5 km/h) and 65 mph (104,5 km/h). The results showed a significant effect for an increase in the shoulder width for roads with a speed limit of 50 mph and 65 mph and indicate a decrease of crashes for an increase of the shoulder width.

A paper by Ma et al. (2008) presents a multivariate Poisson-lognormal regression model for the prediction of crashes by severity on rural two-lane roads, using Bayesian methods. The study includes segment length, horizontal curve length, degree of curvature, vertical curve length, vertical grade, surface width, speed limit, AADT and road type as independent variables. The study distinguishes several severity levels including, fatal, disabling injury, non-disabling injury, possible injury, property damage only and total crashes. The reference shoulder width is defined as 2,1 ft (0,6 m) which are increased with 5 ft (1,5 m). The results per severity level are given as the percentage change in crash rates per 100 million vehicle miles travelled (VMT). The percentage of all severity levels are found to be negative, implying a decrease in the number of crashes for an increased shoulder width of 5 ft (1,5 m). The results for fatal and disabling injury crashes were found to be insignificant. The other severity levels were found to be significant and their percentage change per 100 million VMT was found to be between -5 and -8%.

2.2 ANALYSIS METHODS AND RESULTS

2.2.1 Introduction

The estimates in the 5 coded studies were subject to different statistical models with different sets of dependent and independent variables and the estimates are not directly comparable. The results do not lend themselves for meta-analysis.

The effects of (paved) shoulders (vs. no shoulders) on 2-lane rural highways can be summarized as follows:

- 4 studies with significant accident reductions for wider shoulders
- 1 study with significant accident reductions for wider shoulders in combination with shoulder rumble strips
- 2 studies with significant increase in accident for narrower shoulders in combination with narrower lanes

Table 1 presents an overview of the main features of coded studies (sample, method, outcome indicator and results).

Table 1 Description of coded studies

Author, Year	Sample and study design	Method of analysis	Outcome indicator	Main result
Park et al. 2014	Observational study including 257 and 676 road segments in Florida for the treated and comparison group. Collected between 2003 and 2012	Before-After and cross-sectional models using empirical bayes method	Crash modification factors (CMFs) for total and single-vehicle run-off road crashes and for total and fatal + injury crashes.	All CMFs are smaller than one, implying crash reduction for wider shoulders. The combination with shoulder rumble strips also proves to lead to crash reductions for all categories.
Gross et al. 2009	Data collected in Pennsylvania and Washington between 1997 and 2006. Including 86.473 crash segments and 129.511 non-crash segments	Matched case-control analysis with a conditional logistic regression model to investigate the relationship between outcome and risk factor	CMFs for total number of crashes	All CMFs for narrower combinations of shoulder and lane width are larger than one, implying an increased number of crashes for narrow shoulders and narrow lanes.
Stamatiadis et al. 2009	Data from California, Minnesota and Kentucky collected during 12 year periods. 2.387 miles of four lane road segments	Negative Binomial model	CMFs for divided and undivided roads, with distinction between multi- single and total crashes	Reference shoulder width was set at 3 ft. All CMFs for narrower shoulders were larger than 1, implying more crashes. All CMFs for wider shoulders were smaller than 1, implying less crashes. Widening of narrow shoulders has more effect compared to widening of less narrow shoulders.
Islam et al. 2014	Data collected between 2009 and 2011 in Connecticut. 949 road segments were identified on two-lane, two-way rural roads and four-lane divided highways.	A negative Binomial (BN) model was used to derive CMFs	CMFs were developed for both multi- and single-vehicle crashes. Further distinction into total and fatal and injury crashes.	Comparison between shoulder widths smaller (reference) and larger (test) than 10 ft (3 m). Results multi-vehicle crashes are insignificant. For single-vehicle crashes results suggest a reduction for wider shoulders.
Ma et al. 2008	A total of 7773 rural two-lane highway segments in Washington state were used, containing 16 fatal, 50 disabling, 180 non-disabling, 175 possible injury and 532 property damage only crashes	Multivariate Poisson-lognormal model using a Gibbs sampler and the Metropolis-Hastings algorithms for crashes on Washington state rural two-lane highways.	Percentage change in crash rates per 100 million vehicle miles travelled for crash severities: fatal, disabling, non-disabling, possible injury, property damage only, and total crashes	Reference shoulder width was set at 2,1 ft and increased with an additional 5 ft. Fatal and disabling crashes were found insignificant. The other severity levels were found to all be negative, -5 à -8%. Implying crash reduction for wider shoulders.

2.2.2 Overall estimate for accident severity

Overall (based on all crashes) the studies seem to suggest that narrow shoulders lead to increased crashes. However, this effect may vary for different study designs and included variables.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature on shoulders and road safety was searched for in the international databases Scopus and TRID on 27 March 2016. Scopus is the largest international peer-reviewed database indexing scientific journals, books and conference proceedings from more than 5,000 publishers. TRID is an integrated database that combines the records from TRB's Transportation Research Information Services (TRIS) Database and the OECD's Joint Transport Research Centre's International Transport Research Documentation (ITRD) Database. TRID provides access to more than one million records of transportation research worldwide.

For Scopus the following query was used to select papers about road safety: ((road and casualt*) or (road and injur*) or (road and accident*) or (road and crash*) or (traffic and injur*) or (traffic and casualt*) or (traffic and accident*) or (traffic and crash*)).

For TRID the following query was used: (collision* or crash* or accident* or injur* or casualt*) AND (traffic or road). Both for Scopus and TRID all search results were filtered on English language only.

The aforementioned queries were combined with a query to select papers relating to the risk factor narrow shoulder:
((narrow AND shoulder) OR (wide AND shoulder) OR (widening AND shoulder) OR (narrow ing AND shoulder) OR "shoulder width" OR "width of the shoulder") AND NOT TITLE-ABS-KEY (fracture OR trauma OR tissue OR disorder* OR surgery))

These queries were combined in Scopus and TRID to search for literature about the risk factor absence of shoulders. Searches were done for Worldwide and Europe. To distinguish literature from Europe and Worldwide, the results were loaded into Mendeley, where the following query was used to identify literature from Europe: (Italy or Ireland or Hungary or Greece or Germany or France or Finland or Estonia or Denmark or Czech or Cyprus or Croatia or Bulgaria or Belgium or Austria or Scotland or England or Britain or United Kingdom or Sweden or Spain or Slovenia or Slovakia or Romania or Portugal or Poland or Netherlands or Malta or Luxembourg or Lithuania or Latvia).

The number of hits for Europe and Worldwide and for Scopus and TRID are presented in table 2.

search no.	Region	Database	hits
#1	Europe	Scopus	24
#2	Europe	TRID	90
#3	Worldwide	Scopus	64
#4	Worldwide	TRID	218

Table 2: *Literature search results*

All abstracts were reviewed on relevance for the risk factor. From reviewing the abstracts a total of 30 publications were selected as the most promising. For 11 of these the full text version could not be retrieved and these were not considered further. From the remaining 16 references, 5 were selected for coding.

3.2 LIST OF STUDIES

3.2.1 Coded studies

The following list contains the references of the coded studies:

Gross, F., Jovanis P, P., Eccles A, K., & Chen, K.-Y. (2009). *Safety Evaluation of Lane and Shoulder Width Combinations on Rural, Two-Lane, Undivided Roads*. Retrieved from http://www.fhwa.dot.gov/publications/research/safety/09031/index.cfm

Islam, M., Ivan, J., Lownes, N., Ammar, R., & Rajasekaran, S. (2014). Developing Safety Performance Function for Freeways by Considering Interactions Between Speed Limit and Geometric Variables. *Transportation Research Record: Journal of the Transportation Research Board*, *2435*(2435), pp 72–81. http://doi.org/10.3141/2435-09

Ma, J., Kockelman, K. M., & Damien, P. (2008). A multivariate poisson-lognormal regression model for prediction of crash counts by severity, using bayesian methods. *Accident; Analysis and Prevention*, *40*(3), 964.

Park J, Abdel-Aty M, Lee C. (2014). *Exploration and comparison of crash modification factors for multiple treatments on rural multilane roadways.* Accident; analysis and prevention.;70:167-77.

Stamatiadis, N., Pigman, J., Sacksteder, J., Ruff, W., & Lord, D. (2009). *Impact of shoulder width and median width on safety*

3.2.2 Selected not coded studies

The following list contains the studies rated as relevant based on the review of abstracts but not coded:

Abdel-Rahim, A., & Sonnen, J. (2012). *Potential Safety Effects of Lane Width and Shoulder Width on Two-Lane Rural State Highways in Idaho*. Retrieved from http://itd.idaho.gov/highways/research/archived/reports/RP200Final.pdf\nhttp://ntl.bts.gov/lib/46000/46300/46364/RP200Final.pdf\nhttps://trid.trb.org/view/1225523

Armour, M., & McLean, J. R. (1983). EFFECT OF SHOULDER WIDTH AND TYPE ON RURAL TRAFFIC SAFETY AND OPERATIONS. *Australian Road Research*, *13*(4), 259–270. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0020906933&partnerID=40&md5=aa880f3d0312158e6b7ebd7092c162f8

Bamzai, R., Lee, Y., & Li, Z. (2011, April). Safety Impacts of Highway Shoulder Attributes in Illinois. *Civil Engineering Studies, Illinois Center for Transportation Series*. University of Illinois, Urbana-Champaign. Retrieved from http://hdl.handle.net/2142/45840

Ben-Bassat, T., & Shinar, D. (2011). Effect of shoulder width, guardrail and roadway geometry on driver perception and behavior. *Accident; Analysis and Prevention*, *43*(6), 2142–52. http://doi.org/10.1016/j.aap.2011.06.004

Dixon, K., Fitzpatrick, K., Avelar, R., Perez, M., Ranft, S., Stevens, R., … Voigt, T. (2015). *Reducing Lane and Shoulder Width to Permit an Additional Lane on a Freeway: Technical Report*. Retrieved from http://tti.tamu.edu/documents/0-6811-1.pdf

Dumbaugh, E. (2006). Design of safe urban roadsides an empirical analysis. *Transportation Research Record*. 1676 Braeburn Drive, Atlanta, GA 30316, United States. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-33845318513&partnerID=40&md5=c2ff9209d95ed8b8cbb9976bc1e6a689

Easa, S. M., & Mehmood, A. (2008). Optimizing Design of Highway Horizontal Alignments: New Substantive Safety Approach. *Computer-Aided Civil and Infrastructure Engineering*, *23*(7), pp 560–573. http://doi.org/10.1111/j.1467-8667.2008.00560.x

Gross, F., & Jovanis, P. P. (2007). Estimation of the safety effectiveness of lane and shoulder width: Case-control approach. *Journal of Transportation Engineering*, *133*(6), 362–369. http://doi.org/10.1061/(ASCE)0733-947X(2007)133:6(362)

Gross, F., & Jovanis, P. P. (2007). Estimation of safety effectiveness of changes in shoulder width with case control and cohort methods. *Transportation Research Record*. Department of Civil and Environmental Engineering, Pennsylvania State University, 212 Sackett Building, University Park, PA 16802, United States. http://doi.org/10.3141/2019-28

Hallmark, S. L., Qiu, Y., Pawlovitch, M., & McDonald, T. J. (2013). Assessing the Safety Impacts of Paved Shoulders. *Journal of Transportation Safety and Security*, *5*(2), pp 131–147. http://doi.org/10.1080/19439962.2012.711438

Hanley, K. E., Gibby, A. R., & Ferrara, T. C. (2000). ANALYSIS OF ACCIDENT-REDUCTION FACTORS ON CALIFORNIA STATE HIGHWAYS. *Transportation Research Record*, (1717), p. 37–45. Retrieved from http://dx.doi.org/10.3141/1717-06

Hansen, G., Garrick W, N., Ivan N, J., & Jonsson, T. (2007). Variation in Free-Flow Speed due to Roadway Type and Roadside Environment (p. 13p). Retrieved from https://trid.trb.org/view/802580

Harwood W, D., Council M, F., Hauer, E., Hughes E, W., & Vogt, A. (2000). *PREDICTION OF THE EXPECTED SAFETY PERFORMANCE OF RURAL TWO-LANE HIGHWAYS*. Retrieved from http://www.fhwa.dot.gov/publications/research/safety/99207/99207.pdf

La Torre, F. (2012). *Forgiving Roadsides Design Guide*. Retrieved from http://www.cedr.fr/home/fileadmin/user_upload/Publications/2013/T10_Forgiving_roadsides.pdf

La Torre, F., Saleh, P., Cesolini, E., & Goyat, Y. (2012). Improving Roadside Design to Forgive Human Errors. In *Procedia - Social and Behavioral Sciences* (Vol. 53, p. pp 235–244). Elsevier. Retrieved from http://dx.doi.org/10.1016/j.sbspro.2012.09.876

Labi A, S. (2006). *Effects of Geometric Characteristics of Rural Two-Lane Roads on Safety*. Retrieved from http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1709&context=jtrp

Le Q, T., & Porter Jon, R. (2013). Safety Effects of Cross-Section Design on Urban and Suburban Roads (p. 17p). Retrieved from https://trid.trb.org/view/1242979

Li, Z., Lee, S. H., Lee, Y., Zhou, B., & Bamzai, R. (2011). A methodology for assessing safety impacts of highway shoulder paving. In *1st Congress of the Transportation and Development Institute of ASCE* (pp. 1105–1117). Department of Civil, Architectural and Environmental Engineering, Illinois Institute of Technology, Chicago, IL 60616, United States. http://doi.org/10.1061/41167(398)106

Park, J., & Abdel-Aty, M. (2016). Safety Effects for Widening Shoulder Width on Rural Multi-lane Roadways in Developing Crash Modification Functions using Multivariate Adaptive Regression Splines (p. 18p). Retrieved from http://docs.trb.org/prp/16-0676.pdf

Parkhill, M., & Bahar, G. (2006). Managing run-off-road collisions: Engineering treatments with AMFs. In *TAC/ATC 2006 - 2006 Annual Conference and Exhibition of the Transportation Association of Canada: Transportation Without Boundaries*. Transportation Association of Canada (TAC). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-84898421842&partnerID=tZOtx3y1

Prinsloo, B., & Goudanas, C. (2003). Development of a crash prediction model for rural roads in NSW. In *Proceedings - Conference of the Australian Road Research Board* (Vol. 21, pp. 57–65). Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-1842612450&partnerID=tZOtx3y1

Schrock, S., Parsons, R., & Zeng, H. (2011). Estimation of Safety Effectiveness of Widening Shoulders and Adding Passing Lanes on Rural Two-Lane Roads. *Transportation Research Record*, (2203), 57–63. http://doi.org/10.3141/2203-07

Shaon Rahman, M. R., & Qin, X. (2016). Quantifying Safety Effects of Rural Roadway Features Using Mixed Distribution Generalized Linear Models (p. 14p). Retrieved from https://trid.trb.org/view/1394425

Srinivasan, R., & Carter, D. (2011). *Development of Safety Performance Functions for North Carolina*. Retrieved from http://www.ncdot.org/doh/preconstruct/tpb/research/download/2010-09finalreport.pdf

Stamatiadis, N., Lord, D., Pigman, J., Sacksteder, J., & Ruff, W. (2011). Safety impacts of design element trade-offs for multilane rural highways. *Journal of Transportation Engineering*, *137*(5), 333–340. http://doi.org/10.1061/(ASCE)TE.1943-5436.0000221

3.2.3 References on general background

iRap (2013). Road Attribute Risk Factors: Paved Shoulder Width. Factsheet, iRap, May 2013.UK, Hampshire: iRap.

Labi, S. (2006). *Effects of geometric characteristics of rural two-lane roads on safety. Report No. FHWA/IN/JTRP-2005/2*. Indiana, West Lafayette: Purdue University.

Ogden, K.W. (1996). The effects of paved shoulders on accidents on rural highways. *Accident. Analysis and Prevention*, *29*, 353-362.

RISER (2006). *D06: European Best Practice for Roadside Design: Guidelines for Roadside Infrastructure on New and Existing Roads*. RISER deliverable, February 2006. Gothenburg: Chalmers University of Technology/RISER.

Stamatiadis, N., Pigman, J., Sacksteder, J., Ruff, W., & Lord, D. (2009*). Impact of shoulder width and median width on safety*. NCHRP Repprt 633. Washington D.C.: Transportation Research Board.

Synopsis 26: Shoulder and roadside deficiencies - Risks associated with safety barriers and obstacles

1 Summary

Usami, D. S., September 2016

Colour Code: Yellow
Most of the studies show that the absence of safety barriers and the presence of obstacles in the roadside seem to affect both the number of crashes and the severity of injuries. Presence and type of obstacle struck and a shortened distance to obstacles tend to increase run-off-road crash frequency and a higher injury risk. However regarding safety barriers, variable effects can be observed.

Keywords: clear-zone; roadside obstacles; run-off-road; safety barriers; crash cushion; guardrail

1.1 ABSTRACT

Safety barriers and obstacles refer to: 1) the presence and type of obstacles in the roadside; 2) the distance between the edge of the road and fixed obstacles; 3) the absence of protection from the obstacles. The Synopsis focuses on the risk aspects of safety barriers and obstacles and does not consider the safety benefits from implementing a safety barrier as a countermeasure. In general, mixed effects of safety barriers and obstacles on road safety are observed. Obstacles close to the road can increase the number of crashes, moreover different obstacles lead to different consequences in case of crash. The shorter the distance to the obstacle the higher is the run-off-road crash frequency and the probability of a severe injury crash. The effect of safety barriers on crash frequency seems to be non-significant, while the effect on crash severity seems to be somewhat unclear. If not adequately protected guardrails and concrete barriers may represent a risk for motorcyclists.

1.2 BACKGROUND

1.2.1 What are safety barriers and obstacles?

Safety barriers and obstacles refer to features on the roadside. In terms of identifying risk the following were considered: 1) the presence and type of obstacles in the roadside; 2) the distance between the edge of the road and fixed obstacles (i.e. width of clear zone[1]); 3) the absence of protection of the obstacles (e.g. safety barriers or crash cushion).

1.2.2 How do safety barriers and obstacles affect road safety?

Along roadways there may be steep slopes, poles, trees and other fixed obstacles, that may cause injuries when crashes occur. Safety barriers (e.g. guardrails) are often installed to protect from collisions with roadside obstacles, but may under certain conditions pose risks to specific road user groups.

These obstacles present hazards to drivers who lose control over the vehicle, particularly when the fixed objects are located too close to the roadway, because there is less space available for recovery.

[1] A clear zone is the unobstructed, traversable area provided beyond the edge of the through traveled way for the recovery of errant vehicles. The clear zone include shoulders and bike lanes, and auxiliary lanes, except those auxiliary lanes that function like through lanes (AASHTO, 2011)

Also the type of obstacle struck and the shape of the terrain along the roadside may lead to a more/less serious crash. For instance, the steeper and higher the slope the higher is the probability of a rollover, and in case of rollover, the probability of being killed or injured increases (Elvik et al, 2009).

A lack of protection from these obstacles (absence of guardrails and/or crash cushions) may increase the severity of injury in case of crash. However, it should be noted that a safety barrier is in itself a fixed obstacle and in some cases it may reduce visibility.

1.2.3 Which safety outcomes are affected by safety barriers and obstacles?

In the international literature, the risk associated with safety barriers and obstacles on road safety has been measured on two basic outcomes, namely crash frequency (number of crashes occurred) or crash severity (severity of injuries of occupants given that a crash has occurred).

1.2.4 How is the effect of safety barriers and obstacles on risk studied?

International literature indicated that the effect on risk of safety barriers and obstacles is usually examined by applying multivariable linear statistical models. In crash frequency models, the relationship between the presence of an obstacle and the number of crashes is investigated with negative binomial models, while in crash severity models, all studies identified applied logistic regression models.

1.2.5 Which factors influence the effect of safety barriers and obstacles on road safety?

Safety barriers and obstacles do not influence road safety in isolation. For example, operating speed and horizontal alignment also have an influence on the effect of safety barriers and obstacles. Even though speed is not put in relation with roadside deficiencies in the identified studies, it is obvious that higher speeds and a poor designed roadside can lead to more severe run-off-road crashes. The location of the obstacle also has an influence. An obstacle located on a curve increases the probability of collision as the steeper the curves on a roadway the more run-off-road crashes are likely to occur. Environmental conditions, such as ice and snow covered pavements, may also increase the probability of a run-off-road. The injury risk depends also on the type of obstacle hit, the characteristics of the road users hitting the obstacle (PTW riders and elderly persons are subjected to more severe injuries in case of impact with a roadside object), the number of vehicle occupants.

1.3 OVERVIEW RESULTS

Most of the studies identified that road deficiencies appear to increase crash frequency and severity. The effects identified can be summarized as follows:

- *Presence and type of obstacle struck*. The presence of an obstacle within 2 meters on one or both roadsides increase the number of run-off-road crashes. The density of obstacles (e.g. group of trees, density of poles) increases the frequency of crashes. In case of encroachment it is more likely to hit a fixed object. Objects leading to higher severity crash outcomes seem to be: trees, utility poles, rock banks, columns and walls. Obstacles showing a lower crash severity in case of impact seem to be: sign supports, fences, ditches. In case of Powered Two Wheelers (PTW) crashes the risk of fatal injury is higher for collisions with roadside objects than collisions with the ground.
- *(Short) Distance to obstacles/safety barrier*. A decrease of the clear zone width or of the distance from outside shoulder edge to fixed obstacles increases the run-off-road crash frequency. The

lower the clear zone width the higher the risk of run-off-road crashes. This result seems to apply both on straight and on curve road segment. Studies refer mostly to rural roads.

- *(Absence of) safety barrier or crash cushion*. One study reported a non-significant increase in the number of run off road crashes in case of the absence of a safety barrier. On the other hand, the effects on crash severity seem to be somewhat unclear, except for PTWs. In this case the risk of fatal injury for motorcycle collisions is higher when hitting a guardrail or a concrete barrier than collisions with the ground. Only one study examined the effects of the absence of a crash cushion showing an increased propensity toward fatal injury.

1.4 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound.

Overall, the topic has not been deeply studied (number of relevant studies is 8 investigating various aspects). Because of the fact that the study designs, the applied methods and the adopted outcome indicators of interest are somewhat heterogeneous and inconsistent, potential transferability of results is unlikely. Moreover, the effect has not been tested under all conditions (e.g. investigation of effects by different user groups, different road areas, only two European studies found, etc.). The studies do not investigate the effects of other factors such as reduced sight conditions along the road with a shortened distance to obstacles.

2 Scientific overview

2.1 LITERATURE REVIEW

Most of the studies identified that safety barriers and obstacles appear to increase crash frequency and severity, for both the number of crashes and the severity of injuries.
The effects identified can be summarized as follows:

- *Presence and type of obstacle struck*. The presence of an obstacle within 0-2 meters on one or both roadsides increase the number of run-off-road crashes (Van Petegem and Wegman, 2014). The density of obstacles (e.g. group of trees, density of poles) increases the frequency of not only run-off-road crashes, but also both injury, severe and total number of crashes (Park and Abdel-Aty, 2015). If an crash with an obstacle is to occur then the probability of an injury increases compared to crashes without obstacles (Lee and Mannering, 2002). In case of PTW crashes, the risk of fatal injury is higher for collisions with roadside objects than collisions with the ground (Daniello and Gabler, 2011). Effects on crash severity of different types of obstacle are not clear in some cases (Holdridge et al., 2004; Lee and Mannering, 2002). Sign supports and fence appear to decrease the probability of possible injury. Utility poles, trees and rock bank/ledge, on the other hand, seem to increase the probability of possible injury and fatal injury. Ambiguous results have been found for ditch, culvert, roadway or construction machinery, and safety barrier. Steep slopes increase the probability of a vehicle rolling over in the event of running off the road. Vehicle rollover increases the driver's risk of fatality or severe injury (Roque et al., 2015).
- *(Short) Distance to obstacles/guardrail*. A reduction of the clear zone width or of the distance from outside shoulder edge to fixed obstacles increases the run-off-road crash frequency (Jurewicz and Pyta,2010; Peng et al., 2011; Park and Abdel-Aty, 2015; Lee and Mannering, 2002). Moreover, the lower clear zone width the higher the risk of run-off-road crashes. Peng et al. (2011) found this result both on tangent and on curve road segment. Elvik et al. (2009) suggest that these results may also include the effects of other factors such as improved sight conditions along the road.
- *Absence of safety barrier or crash cushion*. 1 study (Van Petegem and Wegman, 2014) found the absence of a safety barrier increases the number of run off road crashes. On the other hand, the effect on crash severity is somewhat unclear. According to Lee and Mannering, (2002), the presence of a guardrail increases the probability of disabling/fatal injury. However, Holdridge et al. (2004) found that a safety barrier (guardrail face or concrete barrier) is associated to a higher probability of lower injury severities; while it may increase the probability of property damage only crashes (Roque et al., 2015). Barriers represent a risk for motorcyclists. Daniello and Gabler (2011) found that the risk of fatal injury for motorcycle collisions is higher when hitting a concrete barrier than collisions with the ground. Only one study (Holdridge et al., 2004) examined the effects of the absence of a crash cushion (i.e. presence of a guardrail or bridge rail leading end), indicating an increased propensity toward fatal injury.

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

Overall 8 high quality studies were selected and coded. 5 of the studies investigated the effects on crash frequency (Jurewicz.and Pyta,2010; Peng et al., 2011; Van Petegem and Wegman, 2014; Park and Abdel-Aty, 2015; Lee and Mannering, 2002) and 5 on crash severity (Peng et al., 2011; Daniello and Gabler, 2011; Holdridge et al., 2004; Lee and Mannering, 2002; Roque et al., 2015). In order to examine the relationship between safety barriers and obstacles and outcome indicators, nearly all studies deployed multivariate statistical models (i.e. negative binomial, generalized non-linear models, etc.) as a method of examining the topic and controlled for other geometrical characteristics and traffic flow as well.

Studies on crash frequency used mostly negative binomial regression models (Jurewicz.and Pyta,2010; Peng et al., 2011; Van Petegem and Wegman, 2014; Lee and Mannering, 2002).The studies on crash severity (Peng et al., 2011; Holdridge et al., 2004; Lee and Mannering, 2002; Roque et al., 2015) used a multinomial logit model or a nested logit model. Daniello and Gabler (2011) investigated the effect on fatality risk with a relative risk analysis.

The studies identified mostly have taken into account rural roads. Studies focused on motor vehicle crashes, typically run-off-road crashes. Only one study investigated motorcycle crashes. Most research has been done in the United States (5 studies), but also Australia (1 study), the Netherlands (1 study) and Portugal (1 study) were part of the examination.

Table 1 illustrates an overview of the main features of coded studies (sample, method, outcome and results). Table 10 in Supporting Document presents detailed information on the main outcomes of the coded studies.

Table 1 Description of coded studies

Author(s), Year, Country	**Sample and study design**	**Method of analysis**	**Outcome indicator**	**Main result**
Daniello and Gabler, 2011, United States	Over 20 000 motorcycle crashes with roadside objects and some 440 000 motorcycle crashes with a motor vehicle or hitting the ground. Descriptive observational study.	Relative risk analysis	Relative fatality risk	Motorcycle collisions with roadside objects are more likely to be fatal than collisions with the ground.
Holdridge et al., 2004, United States	The data consisted of 9,723 single-vehicle crashes with a roadside object in the urban setting in Washington (US). Cross-sectional study.	Multivariate nested logit models of injury severity.	Propensity torwards non-Injury, evident injury and disabling injury relative to fatal injury. Propensity torwards property damage only relative to possible injury	Leading ends of guardrails and bridge rails, along with large wooden poles increase the probability of fatal injury. Concrete barriers, beam-guardrail faces, and construction machinery move propensities away from evident and disabling injuries.
Jurewicz.and Pyta,2010, **Australia**	The sample contained 57,925 one-way rural undivided road segments in Victoria (Australia) containing 217 run-off-road casualty crashes to the left. Cross-sectional study.	Negative binomial log-linear model	run-off-road crashes per 60 m segment	A decrease in clear zone width increase the number of crashes per mile.

Lee and Mannering, 2002, United States	The database contains 120 road sections of highway in Washington State (US) where 489 run-off-the-road crashes occurred during 1994-1996. The paper does not specify the number of rural road sections considered in the study (according to some calculation they should be 76, with 241 run-off-road crashes.). Cross-sectional study.	Two types of models were developed: a negative binomial model of crash frequency and a nested logit model of crash severity.	Run-off-roadway crash frequency; Possible injury probability; Crash severity probability	Cut side slope and isolated trees increase run-off-road crash frequency. Distance to light poles or to guardrail decreases rural section run-off-road crash frequencies. Sign supports decrease the probability of possible injury while Culvert and Utility poles increase the probability of possible injury. Guardrail increase the probability of disabling/fatal injury. Miscellaneous fixed objects increase the probability of no evident injury while Tree group decreases the probability of no evident injury.
Park and Abdel-Aty, 2015, United States	A total of 222 rural undivided four-lane roadway segments in US with 81.758 miles in length were identified as target sites. Cross-sectional study.	Generalized Linear model (GLM) with negative binomial	Predicted crash frequency on road segment	(1) increase of distance to poles, (2) increase of distance to trees and (3) decrease of poles density reduce crash frequency.
Peng et al., 2011, United States	The database contains 245.3 mi of roadway in Texas (US) divided into 501 rural road sections where 197 single vehicle run-off-the-road crashes occurred during 2003-2008. Cross-sectional study.	Negative binomial model of crash frequency and multinomial logit model of crash severity.	Number of crashes per mile and probability of the occurrence of crash severity K, A, B*	If the lateral clearance decreases, then the single vehicle run-off-the-road crash frequencies increases, both on tangent and curve segments.
Roque et al., 2015, Portugal	764 single-vehicle ran-off-road (ROR) crashes that occurred on Portuguese freeways during the years 2009 and 2010. Cross-sectional study.	Multinomial logit models and Mixed logit model	Probability of injury for the driver and the most severely injured occupant	ROR crashes involving slopes increase the risk of fatality for the driver. Higher propensity for PDO ROR crashes is associated with the presence of metal safety barriers. Obstacles increase the risk of fatal and severe injury
Van Petegem and Wegman, 2014, Netherland	A total of 7,347 road sections of 100 meters in Netherlands are considered. Cross-sectional study.	Negative Binomial regression	Crash frequency	The presence of a barrier reduces the number of run off road crashes. The presence of an obstacle within 0-2 m on one or both roadsides increase the number of run-off-road crashes

* Fatality (K),Incapacitating injury (A), Nonincapacitating Injury (B)

2.3 RESULTS

A meta-analysis cannot be carried out because a minimum required number of studies is not achieved, in particular:

a) At least 3 studies did not use the same model form
b) The sampling frames were not similar in all cases
c) heterogeneous exposure variables adopted

A vote-count analysis has been undertaken studying the total number of effects according to the presence and type of obstacle struck, the distance to obstacles/safety barrier and the presence of guardrail or crash cushion. Totally 60 effects have been identified, 27 are related to an increased risk, 23 to a decreased risk while 10 are linked to a not significant effect. Results are distinguished by crash frequency, crash severity and crash type (Table 2).

Presence and type of obstacle struck. The presence and type of obstacle increase the number of run-off-road crashes, total, severe and injury crashes (100% of identified effects). The presence and type of obstacles (e.g. tree, signpost, utility pole, etc.) also affect crash severity. Different object struck lead to different consequences. Objects leading to higher severity (52% of effects) seem to be trees, utility poles, rock banks, columns and walls. Obstacles showing a lower severity in case of impact (32% of effects) seem to be sign supports, fences, ditches. In case of PTW crashes the risk of fatal injury is higher for collisions with roadside objects than collisions with the ground.

(Short) Distance to obstacles/safety barrier. The distance between the edge of the road and the obstacle influences the probability of colliding with the obstacle/safety barrier. A decrease of this distance increases the run-off-road crash frequency and also the total crash frequency (75% of identified effects). This result seems to apply both on tangent and on curve road segment. The shorter the distance the higher is the probability of a severe injury crash (100% of identified effects).

Absence of safety barrier or crash cushion. Only one study was found which investigates the effect of safety barriers on crash frequency. It reported a non-significant increase of the number of run off road crashes in case of the absence of a safety barrier. The effect on crash severity seems to be somewhat unclear: 3 effects relate to a higher injury risk on roads without safety barrier and 2 effects report a lower injury risk. The first 3 effects relate to concrete or metal guardrail face and are coherent with the results of the evaluation studies of the effectiveness of safety barriers (Elvik et al. 2009).The other 2 effects refer to two different safety barriers: guardrail and crash cushion. In the first case, the presence of guardrails in the roadway section increased the chance of the crash being a disabling injury/fatality. This finding may be however be linked to the specificities of the study as data are limited to a single roadway (State Route 3 in Washington State). In the latter case the absence of a crash cushion appears to lead to an increased propensity toward fatal injury. The finding is in line with other evaluation studies (Elvik et al. 2009). When focusing on PTWs the effects seem to be clearer. In this case the risk of fatal injury for motorcycle collisions is higher when hitting a concrete barrier rather than collisions with the ground (100% of identified effects).

Table 2 Vote-count analysis results for crash frequency and crash severity by crash type

Etichette di riga	Total number of effects	Result (number of effects)*			Result (% of effects)	
		↗	-	↘	↗	↘
Presence and type of obstacle struck	**32**	**22**	**3**	**7**	**69%**	**22%**
Crash frequency	**7**	**7**			**100%**	**0%**
ROR crash / Crash into fixed objects	4	4			100%	0%
Total crashes	1	1			100%	0%
Total Injury crashes	1	1			100%	0%
Total Severe crashes	1	1			100%	0%
Crash severity	**25**	**16**	**3**	**6**	**56%**	**32%**
ROR crash / Crash into fixed objects	23	12	3	8	52%	35%
Motorcycle crashes	2	2			100%	0%
(Short) Distance to obstacle/barrier	**19**	**15**	**4**	**0**	79%	0%
Crash frequency	**16**	**12**	**4**		75%	0%
ROR crash / Crash into fixed objects	10	9	1		90%	0%
Total crashes	2	2			100%	0%
Total Injury crashes	2	1	1		50%	0%
Total Severe crashes	2		2		0%	0%
Crash severity	**3**	**3**			100%	0%
ROR crash / Crash into fixed objects	3	3			100%	0%
(Absence) of Safety barrier/Crash cushion	**9**	**4**	**2**	**3**	**44%**	**33%**
Crash frequency	**1**		**1**		**0%**	**0%**
ROR crash / Crash into fixed objects	1		1		0%	0%
Crash severity	**8**	**5**	**1**	**2**	**38%**	**50%**
ROR crash / Crash into fixed objects	6	3	1	2	50%	33%
Motorcycle crashes	2	2			100%	0%

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

2.4 CONCLUSION

Studies on the road safety effect of the absence of safety barriers and the presence of obstacles in the roadside investigate three main aspects: the presence and type of obstacle struck, the distance to obstacles or to a safety barrier and the absence of safety barrier or crash cushion.

It can be concluded that mixed effects of safety barriers and obstacles on road safety are observed. An obstacle within 2 meters in the roadside may increase the number of crashes, moreover different obstacles lead to severe or less severe crashes. Short distances to the obstacle increase run-off-road crash frequency and the probability of a severe injury crash. The effect of safety barriers on crash frequency seems to be not-significant, while the effect on crash severity seems to be somewhat unclear. If not adequately protected guardrails and concrete barriers may represent a risk for motorcyclists.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The literature search was conducted in March-April 2016. The search strategy aimed at identifying the best quality and recent studies to estimate the effect of this risk factor. In general, only recent journal studies (after 1989) in the field of Engineering and Social science were initially considered from "Scopus" and "TRID" database. Search terms used to identify relevant papers included but were not limited to: "Obstacles"; "Guardrail"; "Crash Cushion"; "Clear zone"; "Horizontal clearance". Detailed search terms, as well as their linkage with logical operators and combined queries are shown in the following tables. A total of 312 pieces of potentially relevant research were identified. After a preliminary abstract screening text 19 were found to be mostly relevant to the topic.

However, after a full-text screening 15 were judged not suitable for coding (specific effect not reported, topic not specifically addressed etc.). The remaining 4 was included in the synopsis. Key criteria of the text screening included: relevance (whether the research addresses safety barrier and obstacles risk factor), results are not based on crashes, no peer-review.

Other already known or occasionally found studies as well as studies found in the literature search for other topics and including effects for safety barrier and obstacles were added as additional studies (4).

Table 3: Scopus **Date:** 30th of March 2016

search no.	search terms / operators / combined queries	hits
#1	("Roadside") AND ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "risk")	1.319
#2	"Obstacles" OR "tree" OR "pole" OR "fixed object"	746.562
#3	#1 AND #2	**114**

Table 4: TRID (trid.trb.org) **Date:** 20th of April 2016

search no.	search terms / operators / combined queries	hits
#1	roadside obstacles risk accident	**33**

Table 5: SWOV factsheets **Date:** 20th of April 2016

search no.	search terms / operators / combined queries	hits
#1	obstacles	**2**

Table 6: Scopus **Date:** 30th of March 2016

search no.	search terms / operators / combined queries	hits
#1	("Roadside") AND ("road safety" OR "traffic accident" OR "road crash" OR "road accident" OR "risk")	1.319
#2	"Guardrail" OR "Crash Cushion"	831
#3	#1 AND #2	**50**

Table 7: TRID (trid.trb.org) **Date:** 20th of April 2016

search no.	search terms / operators / combined queries	hits

#1	guardrails risk road accident	**33**

Table 8: Absence of clear-zone - Scopus **Date:** 25th of March 2016

search no.	search terms / operators / combined queries	hits
#1	("clear zone*" OR "horizontal clearance" OR "roadside*" OR "shoulder*" OR "slope*" OR "obstacle*" OR "recoverable") W/2 ("run-out" OR "run-off-road" OR "absence" OR "lack" OR "miss")	**17**

Table 9: Absence of clear-zone - TRID database

search no.	search terms / operators / combined queries	hits
#1	"clear zone"	**63**

8 relevant studies were identified after the reference lists of studies were examined. No "grey" literature was examined. No meta-analyses were found.

3.2 DETAILS OF ANALYSIS RESULTS

Table 10 presents information on the main outcomes of coded studies on safety barriers and obstacles.

Table 10 Main outcomes of coded studies for safety barriers and obstacles

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects*		Main outcome -description
Daniello and Gabler, 2011, United States	Object struck: Guardrail	Relative fatality risk / PTW crashes with roadside objects	↗	7,184	Motorcycle collisions with guardrail were 7 times more likely to be fatal than collisions with the ground
	Object struck: Concrete barrier	Relative fatality risk / PTW crashes with roadside objects	↗	4,100	Motorcycle collisions with concrete barrier were 4 times more likely to be fatal than collisions with the ground
	Object struck: Sign	Relative fatality risk / PTW crashes with roadside objects	↗	10,900	Motorcycle collisions with sign were 11 times more likely to be fatal than collisions with the ground
	Object struck: Tree	Relative fatality risk / PTW crashes with roadside objects	↗	14,614	Motorcycle collisions with tree were almost 15 times more likely to be fatal than collisions with the ground
Holdridge et al., 2004, United States	Struck a Wood or metal sign post or guide post	Crash severity / Non-Injury; Evident Injury; Disabling Injury vs Fatal injury	↘	0,5178	Increased propensity torward Non-Injury (and simutaneously away from fatal injury)
	Struck a Roadway ditch, culvert end, or other appurtenance in ditch	Crash severity / Non-Injury; Evident Injury; Disabling Injury vs Fatal injury	↘	0,6546	Increased propensity toward Non-Injury (and simultaneously away from fatal injury)

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects*		Main outcome -description
	Struck a Guardrail or bridge rail Leading End	Crash severity / Non-Injury; Evident Injury; Disabling Injury vs Fatal injury	↗	-2,0553	Decreased propensity toward Non-Injury; Evident Injury; Disabling Injury and increased propensity toward fatal injury
	Struck a Guardrail face	Crash severity / Non-Injury; Evident Injury; Disabling Injury vs Fatal injury	↘	-0,2446	Decreased propensity torward Evident and Disabling Injury. Propensity torward fatal injury is not significant.
	Struck a Concrete barrier	Crash severity / Non-Injury; Evident Injury; Disabling Injury vs Fatal injury	↘	-0,2445	Decreased propensity torward Evident Injury. Propensity torward fatal injury is not significant.
	Struck a Rock bank or ledge	Crash severity / Non-Injury; Evident Injury; Disabling Injury vs Fatal injury	↗	0,9888	Increased propensity toward Evident Injury
	Struck a Roadway or construction machinery struck	Crash severity / Non-Injury; Evident Injury; Disabling Injury vs Fatal injury	-		Ambiguos result: decreased propensity torward Evident Injury and simutaneously increased torward fatal injury (not significant: few observations).
	Struck a Tree or stump, pole (light, utility, railway, traffic, overhead), or sign box	Crash severity / Non-Injury; Evident Injury; Disabling Injury vs Fatal injury	↗	-1,0152	Decreased propensity torward Non-Injury, Evident and Disabling Injury and simutaneously increased torward fatal injury
	Struck column/wall (object is a retaining wall, bridge abutment, column, pier, or pillar)	Crash severity / Property damage vs Possible injury	↗	-0,3279	Decreased propensity torward property damage only and simutaneously torward possible injury
	Struck a fence	Crash severity / Property damage vs Possible injury	↘	0,5567	Increased propensity torward property damage only and simutaneously away from possible injury
	Struck a Wood or metal sign post or guide post	Crash severity / Property damage vs Possible injury	↘	0,4888	Increased propensity torward property damage only and simutaneously away from possible injury
	Struck a Rock bank or ledge	Crash severity / Property damage vs Possible injury	↗	-0,3179	Decreased propensity torward property damage only and simutaneously increased torward possible injury
Jurewicz.and Pyta,2010, **Australia**	Clear zone ≤ 2 m	Run-off-road crashes per 60 m segmet	↗	0,786	Road sections with clear zone less than 2 m have a crash likelihood 2.2 times higher than sections with a clear zone of 8 m or wider.

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects*		Main outcome -description
	Clear zone 2 – 4 m	Run-off-road crashes per 60 m segmet	↗	0,473	Road sections with clear zone of 2 to 4 m have a crash likelihood 1.6 times higher than sections with a clear zone of 8 m or wider.
	Clear zone 4 – 8 m	Run-off-road crashes per 60 m segmet	↗	0,238	Road sections with clear zone of 4 to 8 m have a crash likelihood 1.3 times higher than sections with a clear zone of 8 m or wider.
Lee and Mannering, 2002, United States	Cut side slope indicator	Accident frequency / run-off-roadway	↗	1,1280	the presence of cut-slopes in the roadway right-of-way contributed to increasing run-off-roadway crash frequency.
	Distance from outside shoulder edge to light poles (m)	Crash frequency / run-off-roadway	↗	-0,0290	as the distance from outside shoulder edge to luminaire poles decreased, Rural section run-off-roadway crash frequencies (non-zero state) increased
	Number of isolated trees in a section	Crash frequency / run-off-roadway	↗	0,0860	the number of isolated trees contributed to increasing run-off-roadway crash frequency.
	Distance from outside shoulder edge to guardrail (m)	Crash frequency / run-off-roadway	↗	-0,3200	as the distance from outside shoulder edge to guardrail decreased, Rural section run-off-roadway crash frequencies (non-zero state) increased
	Culvert indicator	Possible injury probability / run-off-roadway	↗	1,550	Increases the probability of possible injury
	Sign support indicator	Possible injury probability / run-off-roadway	↘	−1,805	Decreases the probability of possible injury
	Utility pole indicator	Possible injury probability / run-off-roadway	↗	1,918	Increases the probability of possible injury
	Instrumented guardrail indicator	Disabling injury/Fatality probability / run-off-roadway	↗	0,723	Decreases the probability of disabling/fatal injury
	Miscellaneous fixed object indicator	No evident injury probability / run-off-roadway	↗	0,990	Increases the probability of no evident injury
	Sign support indicator	No evident injury probability / run-off-roadway	↘	0,890	Increases the probability of no evident injury
	Tree group indicator	No evident injury probability / run-off-roadway	↗	−1,404	Decreases the probability of no evident injury
	Utility pole indicator	No evident injury probability / run-off-roadway	↘	0,764	Increases the probability of no evident injury

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects*		Main outcome -description
Park and Abdel-Aty, 2015, United States	Poles density (PD)	Crash frequency / Total crashes	↗	0,194	Significant negative effect on road safety
	Distance to poles (DP)	Crash frequency / Total crashes	↗	-0,1471	Significant positive effect on road safety
	Distance to trees (DT)	Crash frequency / Total crashes	↗	-0,0288	Significant positive effect on road safety
	Poles density (PD)	Crash frequency / Injury (KABC) crashes	↗	0,0174	Significant negative effect on road safety
	Distance to poles (DP)	Crash frequency / Injury (KABC) crashes	↗	-0,1107	Significant positive effect on road safety
	Distance to trees (DT)	Crash frequency / Injury (KABC) crashes	-	-	Non-significant effect on road safety
	Poles density (PD)	Crash frequency / Severe (KAB) crashes	↗	0,0211	Significant negative effect on road safety
	Distance to poles (DP)	Crash frequency / Severe (KAB) crashes	-	-	Non-significant effect on road safety
	Distance to trees (DT)	Crash frequency / Severe (KAB) crashes	-	-	Non-significant effect on road safety
	Poles density (PD)	Crash frequency / Run off road crashes	↗	0,0194	Significant negative effect on road safety
	Distance to poles (DP)	Crash frequency / Run off road crashes	↗	-0,2496	Significant positive effect on road safety
	Distance to trees (DT)	Crash frequency / Run off road crashes	-	-	Non-significant effect on road safety
Peng et al., 2011, United States	Lateral clearance	Crash rate / All segments	↗	-0,0206	If the lateral clearance decreases, then the single vehicle run-off-the-road crash frequencies increases.
	Lateral clearance	Crash rate / Tangent segments	↗	-0,0123	If the lateral clearance decreases, then the single vehicle run-off-the-road crash frequencies increases.
	Lateral clearance	Crash rate / Horizontal curves	↗	-0,0246	If the lateral clearance decreases, then the single vehicle run-off-the-road crash frequencies increases.
	Lateral clearance	Probability of the occurrence of crash severity k / all segments	↗	-0,0238	If the lateral clearance decreases, then the probability of a fatal injury in a single vehicle run-off-the-road crash increases.

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects*		Main outcome -description
	Lateral clearance	Probability of the occurrence of crash severity a / all segments	↗	-0,0162	If the lateral clearance decreases, then the probability of an Incapacitating injury (A) in a single vehicle run-off-the-road crash increases.
	Lateral clearance	Probability of the occurrence of crash severity b / all segments	↗	-0,0072	If the lateral clearance decreases, then the probability of a non-incapacitating injury (A) in a single vehicle run-off-the-road crash increases.
Roque et al., 2015, Portugal	Slope	Probability of fatal injury / Run-off-road - Driver, Multinomial logit models	↗	1,760	Significant negative effect on road safety
	Barrier	Probability of property damage/ Run-off-road - Driver, Multinomial logit models	↘	0,369	Increased Probability of property damage only crashes
	Barrier	Probability of property damage/ Run-off-road - Driver, Mixed logit model	-	0,497	Non-significant effect on Probability of property damage
	Obstacles	Probability of fatal injury / Run-off-road - Most severely injured occupant, Multinomial logit models	↗	0,402	Significant negative effect on road safety
	Obstacles	Probability of fatal injury / Run-off-road - Most severely injured occupant, Mixed logit	↗	0,815	Significant negative effect on road safety
	Slope	Probability of fatal injury / Run-off-road - Most severely injured occupant, Multinomial logit models	-	1,300	Non-significant effect on road safety
	Slope	Probability of fatal injury / Run-off-road - Most severely injured occupant, Mixed logit	-	1,200	Non-significant effect on road safety
	Obstacles	Probability of severe injury / Run-off-road - Most severely injured occupant, Multinomial logit models	↗	0,402	Significant negative effect on road safety
	Obstacles	Probability of severe injury / Run-off-road - Most severely injured occupant, Mixed logit	↗	0,815	Significant negative effect on road safety
Van Petegem and Wegman, 2014, Netherland	Roadside barrier	Crash frequency / Run-off-road crashes	-	-0.720	Non-Significant effect on road safety
	Obstacle 2m	Crash frequency / Run-off-road crashes	↗	0.400	Significant negative effect on road safety

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

3.3 LIST OF STUDIES

3.3.1 List of considered studies

Bambach, M.R., Mattos, G.A. (2015) Head and Spine Injuries Sustained by Motorcyclists in Head-Leading Collisions With Fixed Roadside Objects" Traffic Injury Prevention 16, Issue 2, 17 February 2015, pp 168-176"

Daniello, A., Gabler, H.C.. (2011).Fatality risk in motorcycle collisions with roadside objects in the United States. Accident Analysis and Prevention 43, Issue 3, pp 1167-1170"

Doecke, S; Woolley, J E. (2011) Further investigation into the effective use of clear zones and barriers in a safe system's context on rural roads. Australasian Road Safety Research, Policing and Education Conference, 2011, Perth, Western Australia, Australia, 2011, 11p

Farah, H., Polus, A., Cohen, M.A. (2007) Multivariate analyses for infrastructure-based crash-prediction models for rural highways. Road and Transport Research, 16 (4), pp. 26-41.

Fitzpatrick, Cole D; Harrington, Curt P; Knodler Jr., Michael A. (2014) The Effects of Clear Zone Size and Roadside Vegetation on Driver Behavior. Transportation Research Board 93rd Annual Meeting, Transportation Research Board, 2014, 15p

Holdridge, J.M., Shankar, V.N., Ulfarsson, G.F. The crash severity impacts of fixed roadside objects (2005). Journal of Safety Research Volume 36, Issue 2, 2005, Pages 139-147

Jurewicz, C; Pyta, V. (2010) Effect of clear zone widths on run-off-road crash outcomes. Australasian Road Safety Research Policing Education Conference, 2010, ARRB Group Limited, 2010

Lee, J., Mannering, F. (2002). Impact of roadside features on the frequency and severity of run-off-roadway accidents: An empirical analysis. Accident Analysis and Prevention, 34 pp 149-161.

Martinez, Cesar J; Noyce, David A; Chitturi, Madhav V. Clear Zone (2009). Policy and Run-Off-Road Crashes. ITE 2009 Annual Meeting and Exhibit, Institute of Transportation Engineers (ITE), 2009, 14p

Maze, Thomas H; Sax, C; Hawkins, Neal R. (2009) .The Safety Benefits Added by Lateral Roadside Clearance to Urban Streets. Urban Transport XV. Urban Transport and the Environment, WIT Press, 2009, pp 619-625

Michie, Jarvis D; Bronstad, Maurice E. (1994) HIGHWAY GUARDRAILS: SAFETY FEATURE OR ROADSIDE HAZARD? Transportation Research Record, Issue 1468, 1994, p. 1-9.

Pardillo-Mayora, J.M., Domínguez-Lira, C.A., Jurado-Piña, R. (201) "Empirical calibration of a roadside hazardousness index for Spanish two-lane rural roads 2010. Accident Analysis and Prevention 42, Issue 6, November 2010, pp 2018-2023

Park J., M. Abdel-Aty. (2015). Assessing the safety effects of multiple roadside treatments using parametric and nonparametric approaches. Accident Analysis & Prevention, October 2015, Pages 203–213

Peng Y., S. R. Geedipally, and D. Lord . (2012). Effect of Roadside Features on Single-Vehicle Roadway Departure Crashes on Rural Two-Lane Roads. Transportation Research Record: Journal of the Transportation Research Board. 2012; 2309: 21–29.

Roque, C., Moura, F., Lourenço Cardoso, J. (2015). Detecting unforgiving roadside contributors through the severity analysis of ran-off-road crashes. Accident Analysis and Prevention, 80, pp 262-273

Sax, Christian R; Maze, Thomas H; Souleyrette, Reginald R; Hawkins, Neal; Carriquiry, Alicia L. (2010). Optimum Urban Clear Zone Distance. Transportation Research Record: Journal of the Transportation Research Board, Issue 2195, 2010, pp 27-35

Stigson, H.a, Ydenius, A.b, Kullgren, A.c (2009)Variation in crash severity depending on different vehicle types and objects as collision partner". International Journal of Crashworthiness, Volume 14, Issue 6, December 2009, Pages 613-622

Van Petegem J.W.H., Wegman F. (2014). Analyzing road design risk factors for run-off-road crashes in the Netherlands with crash prediction models. Journal of Safety Research

Vlahogianni, E.I., Yannis, G., Golias, J.COverview of critical risk factors in Power-Two-Wheeler safety 2012 Accident Analysis and Prevention, Volume 49, November 2012, Pages 12-22.

3.3.2 List of coded studies

A detailed list of studies considered are listed below:

Daniello, A., Gabler, H.C.. (2011).Fatality risk in motorcycle collisions with roadside objects in the United States. Accident Analysis and Prevention 43, Issue 3, pp 1167-1170"

Holdridge, J.M., Shankar, V.N., Ulfarsson, G.F. The crash severity impacts of fixed roadside objects (2005). Journal of Safety Research Volume 36, Issue 2, 2005, Pages 139-147

Jurewicz, C; Pyta, V. (2010) Effect of clear zone widths on run-off-road crash outcomes. Australasian Road Safety Research Policing Education Conference, 2010, ARRB Group Limited, 2010

Lee, J., Mannering, F. (2002). Impact of roadside features on the frequency and severity of run-off-roadway accidents: An empirical analysis. Accident Analysis and Prevention, 34 pp 149-161.

Park J., M. Abdel-Aty. (2015). Assessing the safety effects of multiple roadside treatments using parametric and nonparametric approaches. Accident Analysis & Prevention, October 2015, Pages 203–213

Peng Y., S. R. Geedipally, and D. Lord . (2012). Effect of Roadside Features on Single-Vehicle Roadway Departure Crashes on Rural Two-Lane Roads. Transportation Research Record: Journal of the Transportation Research Board. 2012; 2309: 21–29.

Roque, C., Moura, F., Lourenço Cardoso, J. (2015). Detecting unforgiving roadside contributors through the severity analysis of ran-off-road crashes. Accident Analysis and Prevention, 80, pp 262-273

Van Petegem J.W.H., Wegman F. (2014). Analyzing road design risk factors for run-off-road crashes in the Netherlands with crash prediction models. Journal of Safety Research

ADDITIONAL REFERENCES

AASHTO. (2011). Roadside Design Guide, 4th Edition

Elvik, R. / Høye, A. / Vaa, T. / Sørensen, M. (2009): The Handbook of Road Safety Measures. Second edition. Emerald Group. Bingley

Synopsis 27: Shoulder and roadside deficiencies- sight obstructions (Landscape, Obstacles and Vegetation)

1 Summary

Sgarra, V., September 2016

1.1 COLOUR CODE: YELLOW

Studies results show that a significant negative effect on road safety is determined only in presence of a wider tree offset[1]. The results of the studies on speed and lateral position show only effects in terms of increment or reduction of these two parameters, but not in crash rate. Moreover, the effect of sight obstruction has not been tested under all conditions (e.g. investigation of crash severities by different user groups, different road area, no European studies found, etc.).

1.2 KEYWORDS

Sight obstruction, trees, fixed-objects, road edge; speed; lateral direction, crash rate, crash severity, road-side obstacle, safety barrier.

1.3 ABSTRACT

Roadside elements like vegetation, trees, fixed-objects and landscape play a crucial role in the outcomes of loss-of-control and run-off-the-road crashes and severities. Additionally, they influence the way drivers perceive the road edge and alignment and therefore behaviour. Moreover, some studies show how widening paved shoulders, widening fixed-object offsets, and liveable-streets[2] can also influence the number of crashes and severities. Driver lateral position, speed, and both crash rate and severity are the effects studied. Speed and lateral position results show that drivers significantly decrease their speeds and move toward the centerline of the road when roadside trees are nearer to the edge of the road. Concerning crash rate and severity decrease significantly in liveable streets. Most of the International studies did not identify differences between junctions and roads.

The main statistical method applied in investigating the relationship between such sight obstructions and speed/lateral position was analysis of variance (ANOVA). While, to study the link between crash rate and landscape design elements was used the before-after (landscape treatments) analysis and negative binomial regression models. The studies analysis were focused on urban, suburban and rural road network. Most research was done in United States and only one in Europe (Italy).

1.4 BACKGROUND

1.4.1 What is sight obstruction

Sight obstruction is referring to overgrown vegetation or other objects in the roadside landscape which blocks the vision of road users on the road (both straights and intersections).

[1] Two offsets of the trees from the edge of the road pavement

[2] livable streets, at a minimum, seek to enhance the pedestrian character of the street by providing a continuous sidewalk network and incorporating design features that minimize the negative impacts of motor vehicle use on pedestrians (Duany et al., 2000; Ewing, 1996; Jacobs, 1961)

1.4.2 How does sight obstruction affect road safety?

Most research shows how street trees can pose a potential risk to drivers when placed within proximity to the travelled way. Therefore, limited visibility can adversely affect safety and increases the risk of a collision by reducing reaction times and stopping distances. At the same time, if on one hand studies show this potential risk on the other trees provide psychological and environmental benefits.

Indeed, positive psychological implications such as reduced stress, decreased road rage, alleviated depression, and expedited recovery from injuries have been associated with natural environments (Cackowski , & Nasar, (2003).

1.4.3 Which safety outcomes are affected by sight obstruction?

In the international literature, the effect of sight obstruction on road safety has been measured on two basic outcomes, speed (km/h) and lateral position (m) in terms of distance of the vehicle from the road centreline. The use of crash rate (crashes per one million vehicle miles travelled) has been also observed.

1.4.4 How is the effect of sight obstruction studied?

Most of the International studies considered the effect of sight obstruction on speed and lateral position, most often using a driving simulator. Generally, these two outcomes were studied by applying the analysis of variance (ANOVA). Crash rates are explored with negative binomial regression models, before-after analysis and percentage variation.

1.4.5 Which factors influence the effect of sight obstruction on road safety?

Single geometric elements of the road alignment and setting seem to have an influence on the effect of sight obstruction. Moreover, the distance between the drivers' trajectory and the trees is a significant factor that influences the drivers' choice of speed. Combination of different tree offsets from the road edge and different road cross sections is a significant factor that might increase crash risk. Inappropriate speed and failure to maintain proper lateral position along the roadway alignment may cause a loss of control of the vehicle (Calvi, 2015).

1.5 OVERVIEW RESULTS

1.5.1 Main results

Most of the studies identified show that a sight obstruction caused by trees does not always have a negative effect on road safety. In particular, one study reported that when trees are close to the edge of the road drivers significantly decrease their speeds moving toward the centerline. In all studies analysed there were just one which record a significant negative effect on road safety. Wider is the offsets of the trees from the edge of the road pavement on rural area, higher is crash risk. Moreover, survey results show how street trees contribute positively to a sense of safety. Concerning crash rates, one study analysed the effect of sight obstruction on urban area, and in particular on liveable section of a historical roadway[3]. The results demonstrate that the historic roadway section records fewer total crashes and injurious crashes than rural roads.

[3]Dumbaugh E., 2005 examined the crash performance of state arterial roadways traveling through the National Register–designated historic districts of DeLand and Ocala, Florida.

1.5.2 Transferability

Potential transferability of results is questionable, due to the fact that almost all studies are related to regional and national locations in the United States (e.g. Texas), so findings could be influenced by national road design specifications.

1.5.3 Notes on analysis methods

In general, the coded studies are of sufficient quality and are methodologically sound.

Overall, the topic has not been deeply studied (number of relevant studies is 5). Because of the fact that the study designs, the applied methods and the results are different, then potential transferability of results is unlikely. Moreover, the effect has not been tested under all conditions (e.g. investigation of crash severities by different user groups, different road area, no European studies found, etc.) and more studies on speed and lateral position are needed, since only two relevant studies were found. In summary, different modelling approaches and different indicators were found to lead to unsteady results and for that reason the effect is unclear and needs further examination.

2 Scientific overview

2.1 LITERATURE REVIEW

All studies have investigated the safety implications of roadway vegetation and trees or other roadside objects. These studies were usually based on field investigations, driving simulator research, or survey.

Naderi et al.,2008 used driving simulation to compare driving speed on suburban and urban roads with and without trees along the roadside They found a positive effect on drivers' perception of the safety of roads lined with trees, as the trees aided drivers in sensing the edge of the road. In particular, in this study a reduction of almost 5 km/h in mean speed when trees were present along the suburban landscape was recorded (Calvi, 2015).

Calvi's, study (2015) was focused on the effects of roadside trees on driving performance in a driving simulator. The main findings of the study indicate that, compared with the baseline condition (no trees on the roadside), drivers significantly decrease their speeds and move toward the centerline of the road when roadside trees are nearer to the edge of the road. When trees are far away, drivers adopt significantly higher speeds with respect to the baseline condition (without trees) along with a lower left lateral displacement. This behaviour occurred along all five of the investigated geometries[4], especially on sharp curves. Tree spacing does not significantly affect drivers' speed, but influences the lateral position: drivers move farther from the edge of the road when tree spacing decreases and trees are nearer to each other (Calvi, 2015).

Dumbaugh, 2005, focused his study t to understand the safety impacts, in terms of crash rate, of liveable streetscape treatments on urban roadways, and in particular on historic district. To determine whether the safety performance of Colonial Drive might perhaps be part of a broader safety trend, he examined the crash performance of state arterial roadways traveling through the National Register–designated historic districts of DeLand and Ocala, Florida. The results show that on average, the historic roadway sections reported somewhat fewer total crashes and substantially fewer injurious crashes. Moreover, not a single fatal crash was reported for any of these historic roadway sections during the 5-year analysis period (Dumbaugh, 2005).

Another Dumbaugh's study (2006), aimed to understand better the design of safe roadsides in urban environments, this study used negative binomial regression models to examine the safety effects of three roadside design strategies: widening paved shoulders, widening fixed-object offsets, and providing liveable-street treatments. His model results indicated that of the three strategies, only the liveable-streets variable was consistently and negatively associated with reductions in roadside and midblock crashes. Wider shoulders were found to increase roadside and midblock crashes, while unpaved fixed-object offsets had a mixed safety effect by decreasing roadside crashes but having a slightly positive effect on midblock crashes (Dumbaugh, 2006).

Concerning the nature of the relationship between roadside landscaping and driver safety, Mok et al., 2006, used a comparison of before-and-after crashes as a quantitative measure of roadside greening to test the effect of landscape improvements on driver performance. Research examined

[4] the roadway geometry manipulation included five options: sharp right curve, sharp left curve, gentle right curve, gentle left curve, and tangent.

61 road sections in Texas that were landscape designed as either urban arterials or state highways. The findings of this study show a significant decrease in crash rate after landscape improvements were implemented at the 95% confidence level on 10 urban arterial or highway sites in Texas (Mok et al. 2006).

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

There has been some research completed on sight obstruction and its implication on road safety. 5 high quality studies were selected and coded. 2 studies investigated the effects on speed and lateral position (Calvi., 2015; and Naderi. et al., 2008) and 3 on crash rates (Dumbaugh., 2005 and 2006; Mok. et al., 2006). In order to examine the relationship between sight obstruction and outcome indicators, only 2 studies deployed the same method, while the other 3 studies each applied an independent method.

Studies on speed and lateral position used ANOVA model (Calvi., 2015; and Naderi. et al., 2008).The studies on crash rates used percentage variation and negative binomial regression models (Dumbaugh., 2005 and 2006), and analysis before-after (Mok. et al., 2006). Moreover, Dumbaugh ., 2005, investigated the effect on crash rates categorized by injury severities.

Overall, studies focused on motor vehicle crashes manly on urban and suburban road. Calvi., 2015 analysed only crashes occurred on rural road. 4 studies were conducted in the United States, while only one in another country (Italy).

Table 2 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 2 Description of coded studies

Author(s), Year	Sample and study design	Method of analysis	Outcome indicator	Main result
Calvi., 2015	38 drivers was investigated, 26 men and 12 women. The ranging was from 22 to 47 years.	Analysis of variance (ANOVA). This study utilized a driver simulator	Speed (km/h) and Lateral position (m) in terms of distance from the center of the vehicle to the road centreline.	Drivers significantly decrease their speeds and move toward the centerline of the road when roadside trees are nearer to the edge of the road.
Dumbaugh, 2005	Crashes and vehicle miles travelled (VMT) during the period 1999-2003 in two 0.5-mile sections of state roadways entering its historic district and in 5-mile urban comparison sections of the same roadway.	Percentage variation between the crash performance of sections of the historic district and outside roadside.	Mid-block crashes per 100 million VMT and Mid-block crashes per mile.	On average, the historic roadway sections reported somewhat fewer total crashes and substantially fewer injurious crashes.
Dumbaugh, 2006	109 roadside-related crashes from 1999 to 2003, and 411 midblock, non-intersection crashes during the 5-year analysis period.	Negative binomial regression models.	Roadside crashes and Mid-block crashes.	Liveable-streets variable was consistently and negatively associated with reductions in roadside and midblock crashes. Wider shoulders were found to increase roadside and midblock crashes, and unpaved fixed-object offsets decrease roadside crashes but with a slightly

				positive effect on mid block crashes.
Mok et al., 2006	Overall 5874 crashes at 10 sites for 3–5 year periods before and after landscape intervention were used for analysing crash rate in this research.	Before-After analysis.	Crash rates and number of tree collision.	A significant decrease in crash rate after landscape improvements were implemented at the 95% confidence level on 10 urban arterial or highway sites in Texas.
Naderi. et al., 2008	31 participants ranged from 19 to 51 years old. There were 21 males and 10 females.	Analysis of variance ANOVA and survey (questionnaire). This study utilized a driver simulator	Speed (km/h) and Sense of safety and of edge.	The self-reports indicate that trees contribute to a sense of safety. The significant reduction in driver speeds in the suburban condition indicates that street trees may provide positive operational values.

2.3 RESULTS

Most of the studies identified that sight obstruction caused by trees appears to have no negative effects on road safety. The effects individuated can be summarized as follows:

- 2 studies (Calvi, 2015; Naderi. et al., 2008) show a significant reduction of driver speed if trees are nearer to the edge of the road. When treesare far away, drivers adopt significantly higher speeds with respect to the baseline condition (no trees on the roadside) along with a lower left lateral displacement. When trees are present on the roadside: drivers move towards the center of the road, away from the trees, creating a potentially dangerous condition for head-on collisions, especially when visibility restrictions do not allow the driver to see a vehicle coming from the opposite direction (i.e., along vertical crests and horizontal curves). The situation is even more critical along sharp left curves, as drivers cut the trajectory, move toward the inner edge of the roadway, and almost invade the opposite lane.
- 2 studies (Dumbaugh 2006;Mok et al., 2006) show a significant decrease in crash rate after roadside landscape improvements . Moreover, Dumbaugh, 2006, shows that wider shoulders increase roadside and midblock crashes, while unpaved fixed-object offsets decrease roadside crashes but with a slightly positive effect on mid block crashes.
- Dumbaugh, 2005, assessed the effects of liveable streetscape on safety of urban roadways. They found a significant positive effect on road safety in liveable section recording fewer total crashes and substantially fewer injurious crashes. There can be little doubt that the liveable section is the safer roadway in terms of crash severities.

A meta-analysis cannot be carried out because of different sampling frames and use of model form in all cases.

Table 2 presents information on the main outcomes of coded studies

Table 2 Main outcomes of coded studies

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects[5]		Main outcome -description
Calvi, 2015	Tree spacing	Speed (km/h)		-	Non-significant effect on road safety
	Tree spacing	Lateral position (m)		-	Significant positive effect on road safety
	Tree offset/geometric element (1.5 m; sharp right curve)	Speed (km/h)	↘	-7,500 (compared to the case of no trees)	If tree offset is 1.5 m and in case of sharp right curve the drivers speed is expected to decrease
	Tree offset/geometric element (1.5 m; sharp left curve)	Speed (km/h)	↘	-10,000 (compared to the case of no trees)	If tree offset is 1.5 m and in case of sharp left curve the drivers speed is expected to decrease
	Tree offset/geometric element (1.5 m; gentle right curve)	Speed (km/h)	↘	-3,500 (compared to the case of no trees)	If tree offset is 1.5 m and in case of gentle right curve the drivers speed is expected to decrease
	Tree offset/geometric element (1.5 m; gentle left curve)	Speed (km/h)	↘	-4,300 (compared to the case of no trees)	If tree offset is 1.5 m and in case of gentle left curve the drivers speed is expected to decrease
	Tree offset/geometric element (1.5 m; tangent)	Speed (km/h)	↘	-2,700 (compared to the case of no trees)	If tree offset is 1.5 m and in case of tangent section the drivers speed is expected to decrease
	Tree offset/geometric element (4.0 m; sharp right curve)	Speed (km/h)	↗	5,700 (compared to the case of no trees)	If tree offset is 4.0 m and in case of sharp right curve the drivers speed is expected to increase
	Tree offset/geometric element (4.0 m; sharp left curve)	Speed (km/h)	↗	5,600 (compared to the case of no trees)	If tree offset is 4.0 m and in case of sharp left curve the drivers speed is expected to increase
	Tree offset/geometric element (4.0 m; gentle right curve)	Speed (km/h)	↗	6,500 (compared to the case of no trees)	If tree offset is 4.0 m and in case of gentle right curve the drivers speed is expected to increase
	Tree offset/geometric element (4.0 m; gentle left curve)	Speed (km/h)	↗	5,900 (compared to the case of no trees)	If tree offset is 4.0 m and in case of gentle left curve the drivers speed is expected to increase
	Tree	Speed (km/h)	↗	1,200	If tree offset is 4.0 m and in case

[5] ↘ Significant positive effect on road safety
↗ Significant negative effect on road safety

	offset/geometric element (4.0 m; tangent)			(compared to the case of no trees)	of tangent section the drivers speed is expected to increase
	Tree offset/geometric element (1.5 m; sharp right curve)	Lateral position (m)	↘	-7,900	If tree offset is 1.5 m and in case of sharp right curve the drivers distance from the center line of the road is expected to decrease
	Tree offset/geometric element (1.5 m; sharp left curve)	Lateral position (m)	↘	-5,200	If tree offset is 1.5 m and in case of sharp left curve the drivers distance from the center line of the road is expected to decrease
	Tree offset/geometric element (1.5 m; gentle right curve)	Lateral position (m)	↘	-7,200	If tree offset is 1.5 m and in case of gentle right curve the drivers distance from the center line of the road is expected to decrease
	Tree offset/geometric element (1.5 m; gentle left curve)	Lateral position (m)	↘	-5,900	If tree offset is 1.5 m and in case of gentle left curve the drivers distance from the center line of the road is expected to decrease
	Tree offset/geometric element (1.5 m; tangent)	Lateral position (m)	↘	-11,00	If tree offset is 1.5 m and in case of tangent section the drivers distance from the center line of the road is expected to decrease
	Tree offset/geometric element (4.0 m; sharp right curve)	Lateral position (m)		0,400	Non-significant effect on road safety
	Tree offset/geometric element (4.0 m; sharp left curve)	Lateral position (m)		-7,000	Non-significant effect on road safety
	Tree offset/geometric element (4.0 m; gentle right curve)	Lateral position (m)		-0,500	Non-significant effect on road safety
	Tree offset/geometric element (4.0 m; gentle left curve)	Lateral position (m)		-3,600	Non-significant effect on road safety
	Tree offset/geometric element (4.0 m; tangent)	Lateral position (m)		-3,900	Non-significant effect on road safety
Dumbaugh., 2005	Liveable section	All crash severities (Mid-block crashes per 100 million VMT)	↘	-10,700	All crash severities decrease in liveable section
	Liveable section	Injury (Mid-block crashes per 100 million VMT)	↘	-23,600	Injuries decrease in liveable section
	Liveable section	Fatal (Mid-block crashes per 100 million VMT)	↘	-100,00	Fatalities decrease in liveable section

	Liveable section	All crash severities (Mid-block crashes per mile)	↘	-8,300	All crash severities decrease in liveable section
	Liveable section	Injury (Mid-block crashes per mile)	↘	-29,800	Injuries decrease in liveable section
	Liveable section	Fatal (Mid-block crashes per mile)	↘	-100,00	Fatalities decrease in liveable section
Dumbaugh, 2006	Liveable-streetscape treatments	Roadside crashes	↘	-1,532	A significant decrease in roadside crash rate after liveable-streetscape improvements
	Paved shoulder width >0	Roadside crashes		0,054	Non-significant effect on road safety
	Unpaved fixed-object offset>0	Roadside crashes		−0,038	Non-significant effect on road safety
	Liveable-streetscape treatments	Midblock crashes	↘	−0,649	A significant decrease in midblock crash rate after liveable-streetscape improvements
	Paved shoulder width<0	Midblock crashes	↘	0,003	A significant decrease in midblock crash rate if paved shoulder is <0
	Unpaved fixed-object offset<0	Midblock crashes		0,003	Non-significant effect on road safety
Mok et al., 2006	Landscape treatment	Crash rates		-0,243	A significant decrease in crash rate after landscape treatment
	Landscape treatment	Number of tree collision		70,830	Non-significant effect on road safety
Naderi et al., 2008	City form (suburban)	Sense of safety	↘	0,001 (compared to urban)	Suburban setting contribute to a sense of safety
	Landscape type (with trees)	Sense of safety	↘	0,0001 (compared to the case of no trees)	Street trees contribute to a sense of safety
	City form (suburban)	Sense of edge		-	City form do not influence participants perception of edge
	Landscape type (with trees)	Sense of edge	↘	0,001 (compared to the case of no trees)	Street trees contribute to a sense of safety
	City form (suburban)/ Landscape type (with trees)	Speed (km/h)	↘	4,870 (compared to the case of urban road without trees)	For the suburban landscape, the presence of trees significantly dropped the cruising speed of drivers. However no p-values and standard error of estimate were provided

3 Supporting Document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The search strategy aimed at identifying the best quality and recent studies to estimate the effect of this risk factor. Only recent journal studies (after 1989) in the field of Engineering and Social science were initially considered from the Scopus database (Table 4). Out of 11 potentially eligible studies, all were found to be mostly relevant to the topic. The TRID database (Table 5) was also investigated leading to 19 potentially eligible studies. However, from a full-text screening only 5 was coded and included in the synopsis, while the other papers were eliminated because irrelevant and uncodable.

Table 4 Literature search strategy **(Scopus database)**

search no.	search terms / operators / combined queries	hits
#1	((("sight *" OR "line of sight" OR "sight distance*" OR "view") W/1 ("obstacle" OR "insufficient" OR "limited" OR "restricted" OR "obstruct*")) AND DOCTYPE (ar OR re) AND PUBYEAR > 1989 AND SRCTYPE (j) AND LANGUAGE (english) AND SUBJAREA (engi OR soci))	864
#2	(((road OR traffic) W/1 ("crash*" OR "accident*" OR "collision*" OR "incident*") W/3 ("probability" OR "risk" OR "odd*" OR "likelihood")) AND ("road" OR "traffic") AND DOCTYPE (ar OR re) AND PUBYEAR > 1989 AND SRCTYPE (j) AND LANGUAGE (english) AND SUBJAREA (engi OR soci))	2992
#5	#1 AND #2	11

Table 5 Literature search strategy **(TRID database)**

search no.	search terms / operators / combined queries	hits
#1	"sight obstruct" OR "sight obstruction" OR "restricted sight"	19

The final 5 studies included in the synopsis indicate that the topic has not been thoroughly investigated. The prioritizing criteria adopted on 30 papers were the following:

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

2 of the 5 studies included in the synopsis were identified after the reference lists of studies were examined. No “grey” literature was examined. No meta-analyses were found.

4 List of studies

A detailed list of studies considered in the synopsis are listed below:

1) Calvi A., (2015). Does Roadside Vegetation Affect Driving Performance? Driving Simulator Study on the Effects of Trees on Drivers' Speed and Lateral Position Accident Transportation Research Record Journal of the Transportation Research Board 2518
2) Dumbaugh E., (2005). Safe Streets, Liveable Streets. Journal of the American Planning Association, 71 (3), Pages 283 – 298
3) Dumbaugh E., (2006). Design of Safe Urban Roadsides. An Empirical Analysis. Transportation Research Record: Journal of the Transportation Research Board, No. 1961, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 74–82
4) Mok J. H.,. Landphair H. C.,. Naderi J. R., (2006). Landscape improvement impacts on roadside safety in Texas. Landscape and Urban Planning, Volume 78, Issue 3, 9 November 2006, Pages 263-274
5) Naderi J. R., Byoung S. K, Praveen M, (2008). The Street Tree Effect and Driver Safety. ITE Journal February, Pages 69-73

Synopsis 28: Interchange deficiencies- ramp length

1 Summary

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September 2016

1.1 COLOUR CODE

YELLOW

Explanation: In general, mixed findings were observed, however ramp length is probably risky. While three studies indicate that increased ramp length leads to more serious crashes (an increase in injury severity), the results are not consistent when crash frequency is examined. In this case, four studies were identified with contradictory results; one with positive effect (decrease crashes), two with negative effect (increase crashes) and one with non-significant effect.

1.2 ABSTRACT

In general, short ramps may cause crashes because in this case the driver does not have the time to adjust the speed appropriately. Ramp length is probably risky for road safety although some mixed findings were observed. The results can be differentiated between effects on crash severity and crash frequency. The studies indicate that increased ramp length leads to more serious crashes (i.e. an increase ininjury severity) but the results are significant only at 90% confidence level. The meta-analysis that was conducted revealed a non-significant overall effect for a 95% level. The impact of ramp length on crash frequency is unclear, as two studies indicate that an increase in ramp length leads to more crashes, but opposite or non-significant effects were also found.

KEYWORDS

Ramp length; interchanges; crashes; frequency; severity

1.3 BACKGROUND

1.3.1 How does ramp length affect road safety?

An interchange typically consists of ramps and speed change lanes. Exit ramps are the only controlled accesses from motorways to secondary crossroads and they do generally include a section of curvature. Diverge areas in the vicinity of exit ramps are considered critical elements of motorways, where intensive lane changing maneuvers due to exiting traffic, always cause disturbance to through traffic on the motorway mainlines. This may produce traffic conflicts and increase the occurrence potentialities, or even aggravate the crash injury severity. A recent study found that exit ramps are the risk areas where more crashes on motorways are likely to occur (Chimba et al., 2006). In general, it is intuitive that short ramps may cause crashes because in this case the driver does not have the time to adjust the speed appropriately. However, there is limited information available regarding the effect of ramp length on road crash occurrence and severity.

1.3.2 Definitions of ramp length

This factor is usually defined as "ramp length". It is is a numerical variable and is usually measured in km/mi/m.

1.3.3 Which safety outcomes are affected by ramp length?

In the international literature, the effect of ramp length on road safety has been measured on two basic outcomes, namely crash frequency (number of crashes occurred) or crash severity (severity of injuries of occupants given that an crash has occurred). Only one study examining crash risk was found.

1.3.4 How is the effect of ramp length studied?

International literature indicated that the effect of insufficient ramp length at interchanges is usually examined by applying multivariable linear statistical models. In crash frequency models, the relationship between ramp length and number of crashes is investigated with Poisson or Negative binomial models, while in crash severity models, all studies identified applied ordered probit models. When crash risk is examined (more rarely), the Bayesian logistic model is applied.

1.4 OVERVIEW RESULTS

The effect of ramp length on road safety is heterogenous. Nevertheless, a generally risky impact could be concluded. While it is suggested that that increased ramp length leads to more serious crashes, the results are unclear when crash frequency is examined. In this case, the literature indicates contradictory results which seem to differ across road user types; one study stated that increased ramp length leads to more motorcycle crashes, one study stated that increased ramp length decreases the number of crashes of all passenger vehicles, one study found a non-significant effect on the number of crashes and one study found that increased ramp length increases the number of crashes.

Potential transferability of results is questionable, due to the fact that this risk factor has not been investigated under a wide range of conditions. The main restriction is that the vast majority of studies concern regional locations in the US (e.g. Florida or Washigton state). For these reasons, it was not feasible to produce an overall estimate for the effect of ramp length on the number of crashes.

However, it was attempted to apply a random effects meta-analysis for the effect of ramp length on crash severity, which showed a non-significant effect for a 95% level of confidence. The overall estimate for the beta coefficient for the effect of ramp length on crash severity was found to be 0.1307.

1.5 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodogically sound. The only potential bias indicated is the fact that unobserved heterogeneity that is possibly present in crash severity studies was not accounted for by applying more appropriate stastistical models. Overall, the topic has not been deeply studied. Because of the fact that the study designs, the applied methods and the road user groups of interest are somewhat heterogenous and inconsistent, potential transferability of results is unlikely. Moreover, the effect has not been tested under all conditions (e.g. investigation of crash severity by different road user groups, European studies needed etc.) and more studies on crash frequency are needed, since only two relevant studies were found for different road user groups. Summarizing, different modeling approaches and different indicators were found to lead to inconsistent results and for that reason the effect is unclear and needs further examination.

2 Scientific overview

2.1 LITERATURE REVIEW

Highway interchanges are systems of minor roadways designed to connect two or more major roadways. Ramps are connected to mainline freeways by speed-change lanes that allow entering and exiting vehicles to speed up or slow down without conflicting with ongoing traffic on the freeway mainline areas. Figure 1 illustrates a distinction between on-and off-ramps.

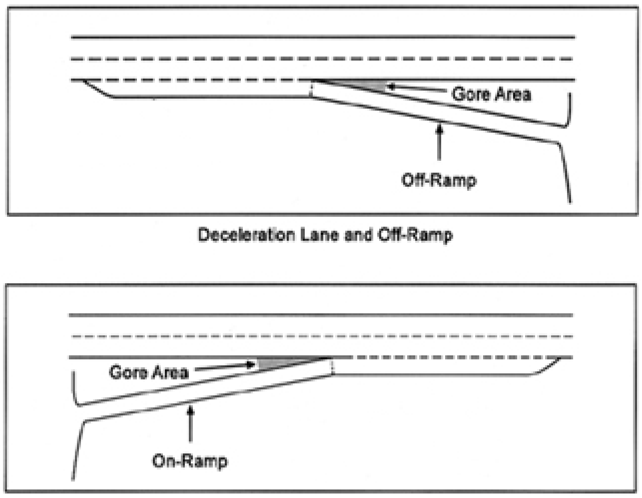

Figure 1 Illustration of on-and off-ramps at interchanges. Source: Bauer and Harwood, 1998.

In order to meet traffic safety and operation requirements, it is important that ramps lanes have the appropriate design and capacity so that entering and exiting vehicles complete sequential maneuvers. Ramp length is the factor that is most commonly examined in the literature as a risk factor. In general, it is intuitive that short ramps may cause road crashes because in this case the driver does not have the time to adjust the speed appropriately. A recent study found that exit ramps are risk areas where more crashes on freeways tend to occur (Chimba et al., 2006). Although the effect of ramp type is adequately examined in the literature, there is limited available information regarding the impact of ramp length on crash occurrence and severity (Chen et al., 2009 and 2011; Li et al., 2012).

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

8 high quality studies were selected and coded. 4 of the studies investigated crash frequency (Bauer and Harwood, 1998; Chen et al., 2011 and 2014; Garnowski and Manner, 2011) and 3 crash severity (Li et al 2012; Wang et al., 2009; Zhang et al., 2011). One study examined crash risk (Wang et al., 2015) but the variable "ramp length" was not significant and was not even retained in the final model. In order to examine the relationship between ramp length and outcome indicators, all studies deployed

multivariable statistical models (i.e. negative binomial, Poisson, etc.) as a method of examining the topic and controlled for other geometrical characteristics and traffic flow as well.

3 out of 4 studies (Bauer and Harwood, 1998; Chen et al., 2011 and 2014), which examine crash frequency, indicate a significant effect on ramp length on interchanges at the state of Washington and state of Florida respectively. More specifically, Bauer and Harwood (1998) considered on-and off-ramps and found a consistent positive correlation of ramp length and and number of crashes for a 90% level. Chen et al. (2011) developed a Poisson model for crash frequency on one-lane exits and found a negative effect of insufficient ramp length. Chen et al., (2014) investigated only motorcycle crashes and indicate that as ramp length increases more motorcycles crashes tend to occur. In addition, different statistical models were applied (Poisson regression vs Negative Binomial). It is noted that both studies examined interchanges at the state of Florida. Therefore, the effect is different for motorcycle crashes than for all passenger vehicles. On the other hand, Garnowski and Manner, (2011) who investigated crash frequency, utilized regional data from Germany and found no effect of ramp length on the number of crashes.

The studies that investigated crash severity used regional data in the US, applied the same statistical models (ordered probit models) and found consistent results. They state that, increased ramp length causes an increase in crash severity. This conclusion is the same accross these studies. However, while Wang et al. (2009) and Li et al. (2012) found strong effects at a 95% level, Zhang et al., (2011) did not found strong effects (at a 90% level only).

Only one study that examined crash risk (probability of crash occurrence) was found; Wang et al. (2015). However, the study showed that there was no effect of ramp length on crash probability as the variable ramp length was not even retained in the final Bayesian logistic model.

Table 1 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 1 Description of coded studies

Author(s), Year	Sample and study design	Method of analysis	Outcome indicator	Main result
Bauer and Harwood, 1998	13706 total crashes in 2000 ramps in Interstates at Washington State, US, for the period 1993-1995	Fixed effects negative binomial models	Crash frequency (number of crashes-fatal and injury, all, not-rear end)	Longer ramps increase the number of crashes
Chen et al., 2011	One-lane exit ramps of Interchanges in the state of Florida, US.352 crashes in 60 sites were considered.	Poisson model	Crash frequency (number of crashes)	Longer exit ramps decrease the number of crashes for all passenger vehicles.
Chen et al., 2014	4 exit ramp types in the state of Florida, US. (573 crashes at 419 total exits). Only motorcycles were considered.	Fixed effects negative binomial model	Crash frequency (number of crashes with motorcycles)	Longer exit ramps increase the number of motorcycle crashes.
Garnowski and Manner, 2011	3048 crashes at 197 ramps in Germany interchanges.	Random parameter Negative binomial model	Crash frequency (number of crashes)	Non-significant effect
Li et al., 2012	5538 accidens at 326 segments in the state of Florida.	Ordered probit model	Crash severity* (5-point scale)	Longer ramps increase severity of crashes

Wang et al., 2009	10,946 crashes at 231 exit segments in the state of Florida, US.	Ordered probit model	Crash severity* (5-point scale)	Longer ramps increase severity of crashes
Wang et al., 2015	137 single-and multi-vehicle crash cases in State Roads 408 (SR408), 417 (SR417), and 528 (SR528), all located in Central Florida.	Bayesian logistic regression model	Crash probability	Non-significant effect (not retained in the final model)
Zhang et al., 2011	5539 crashes 326 motorway segments in Florida, US.	Ordered probit model	Crash severity* (5-point scale)	Longer ramps increase severity of crashes (at a 90% level)

* 1: no injury, 2: possible injury, 3: non incapacitating injury, 4: incapacitating injury, 5: fatal

2.3 ANALYSIS METHODS AND RESULTS

2.3.1 Introduction

The effects identified can be summarized as follows:

- 1 study with a non-significant effect on the number of crashes
- 1 study with a significant decrease in the number of crashes
- 1 study with a significant increase in the number of motorcycle crashes
- 1 study with a significant increase in the number of crashes (at a 90% level)
- 2 studies with a significant increase in crash severity
- 1 study with a weak increase in crash severity (at a 90% level)
- 1 study with a non-significant effect on crash risk

A meta-analysis has been carried out in order to find the overall estimate of ramp length on crash severity. The reasons for this decision is that:

a) A minimum required number of studies is achieved (3)
b) Studies used the same model (ordered probit model)
c) Crash severity was measured in the same way (same 5-point scale)
d) The sampling frames were similar

Another important note considers the nature of these statistical models. Under the parallel lines assumption (proportional odds), the estimate (beta coefficient) of an independent variable is the same for all categories of crash severity.

It was not possible to carry out a meta-analysis for the effect of ramp length on crash frequency because relevant studies used different models or standard errors were not reported.

2.3.2 Overall estimate for crash severity

A random effects meta-analysis was firstly carried out. The overall estimate of the meta-analysis showed a non-significant overall effect (estimate=0.1307, p-value=0.1663). This could be attributed to the fact that one study reported a 90% significance and perhaps to the heterogeneity as well. Table 2 illustrates the main estimates of the random effects meta-analysis, whilst Figure 1 shows the forest plot.

Table 2 Random effects meta-analysis for ramp length effects on crash severity.

Variable	Estimate	Std. Error	p-value	95% CI
Ramp length	0.1307	0.0944	0.1663	(-0.0544, 0.3158)

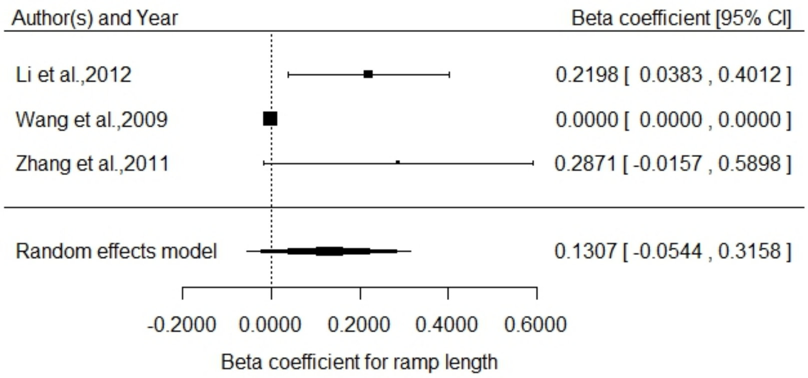

Figure 1 Forest plot of the effect of ramp length (in km) on crash severity.

2.3.3 Heterogeneity

The tau^2 value was 0.0073 indicating the total amount of heterogeneity. I^2 indicates that 75.085% of the total variability in the effect size estimates can be attributed to heterogeneity among the true effects. The Q test is significant (Q=9.0894, p-value = 0.0106) suggesting considerable heterogeneity among the true effects.

2.3.4 Publication Bias

A funnel plot was firstly produced in order to detect potential publication bias. The funnel plot is not symmetric suggesting that there is not strong publication bias.

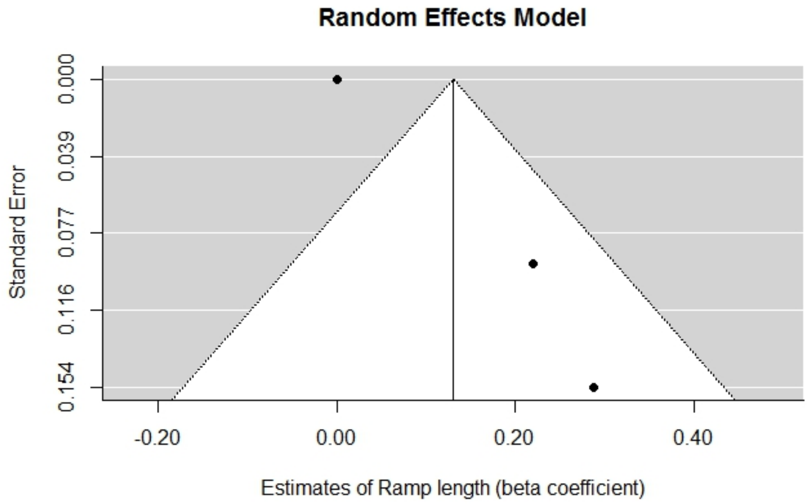

Figure 1 Forest plot of the effect of ramp length (in km) on crash severity.

Another method for testing for publication bias is to test whether the observed outcomes are related to their corresponding standard errors. The regression test showed that a weak existence of publication bias exists (p-value = 0.0771), which is significant only for 90% level. Taking into account that only 3 studies existed, this result should be interpreted with caution. Therefore, it was decided that there was no need to correct for the estimates.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The search strategy aimed at identifying the best quality and recent studies to estimate the effect of this risk factor. In general, only recent journal studies (after 1990) in the field of Engineering were initially considered from the Scopus database. Out of 82 potentially eligible studies, 15 were found to be mostly relevant to the topic. However, after a full-text screening only 8 were coded. However, one more was included in the synopsis because it was informative and considered useful.

Table 1 Literature search strategy 23th of March 2016

search no.	search terms / operators / combined queries	hits
#1	(„interchange" OR „ramp length" OR „interchange ramp length")	1,395
#2	(„interchange ramp length")	83
#3	(„casualties" OR „fatalities" OR „traffic safety" OR „crash" OR „crash risk" OR „severity" OR „frequency" OR „collision" OR „incident" OR „accident")	22,319
#4	#2 AND #3	24
#5	#1 AND #3	**82**

The final 8 studies included in the synopsis indicate that the topic has not been thoroughly investigated. The prioritizing criteria were the following:

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

3 more relevant studies were identified after the reference lists of studies were examined. No "grey" literature was examined. No meta-analyses were found.

3.2 SUMMARY OF RESULTS

The results of the coded studies are summarized in Table 3.

Table 3 Summary results of coded studies

Number	Author(s), Year	Outcome indicator	Quantitative estimate	Effect on road safety
1	Bauer and Harwood, 1998	Crash frequency [number of crashes]	All crashes except rear-end: beta coefficient=4.41, CI[90%]=[2.3,6.56]	↑
			Fatal and injury crashes except rear-end: beta coefficient=2.98,CI[90%]=[0.79, 5.13]	↑

			Fatal and injury crashes:beta coefficient=2.9,CI[90%]=[1.21, 4.61]	↑
2	Chen et al., 2011	Crash frequency [number of crashes]	One lane exits: beta coefficient=-0.7575, p-value=0.0011	↓
3	Chen et al., 2014	Crash frequency [number of crashes]	Beta coefficient=0.35, p-value=0.000	↑
4	Garnowski and Manner, 2011	Crash frequency [number of crashes]	Not retained in the final model	-
5	Li et al., 2012	Crash severity [no injury, possible injury, 3: non-incapacitating injury, incapacitating injury, fatal]	Beta coefficient=0.1365, p-value=0.018	↑
6	Wang et al., 2009	Crash severity [no injury, possible injury, 3: non-incapacitating injury, incapacitating injury, fatal]	Beta coefficient=0.0001, p-value=0.000	↑
7	Wang et al., 2015	Crash risk [probability of crash occurrence]	Not retained in the final model	-
8	Zhang et al., 2011	Crash severity [no injury, possible injury, 3: non-incapacitating injury, incapacitating injury, fatal]	Beta coefficient=0.01783, p-value=0.063	↑

3.3 LIST OF STUDIES

3.3.1 List of coded studies

A detailed list of studies considered are listed below:

1) Zhibin Li, Pan Liu, Wei Wang, Chengcheng Xu (2012). Using support vector machine models for crash injury severity analysis. Accident Analysis and Prevention 45, 478– 486. doi: 10.1016/j.aap.2011.08.016
2) Hongyun Chen, Huaguo Zhou, Jiguang Zhao, Peter Hsu. (2011). Safety performance evaluation of left-side off-ramps at freeway diverge areas. Accident Analysis and Prevention 43, 605–612.
3) Wang, Z., Chen, H., Lu, J.J. (2009). Exploring impacts of factors contributing to injury severity at freeway diverge areas. Transportation Research Record Issue 2102, Pages 43-52.
4) Zhang Yang, Li Zhibin, Liu Pan, Zha Liteng. (2011). Exploring contributing factors to crash injury severity at freeway diverge areas using ordered probit model. 2011 International Conference on Green Buildings and Sustainable Cities. doi: 10.1016/j.proeng.2011.11.2002
5) Martin Garnowski, Hans Manner. (2011). On factors related to car accidents on German Autobahn connectors. Accident Analysis and Prevention 43 (2011) 1864–1871. doi:10.1016/j.aap.2011.04.026.

6) Chen H., Lee, C., Lin P.-S. (2014). Investigation Motorcycle Safety at Exit Ramp Sections by Analyzing Historical Crash Data and Rider's Perception. Journal of Transportation Technologies 04(01):107-115. DOI: 10.4236/jtts.2014.41011.
7) Bauer K.M., Harwood D.W. (1998). Statistical models of accidents on interchange ramps and speed-change lanes. Report No. FHWA-RD-97-106, 1998.
8) Wang L., Shi Q., Abdel-Aty M. (2015). Predicting crashes on expressway ramps with real-time traffic and weather data. Transportation Research Board Annual Meeting, 2015, Washington D.C.

3.3.2 Other references

1) Chimba D., Lan C.J., Li J.B. (2006).Statistical Evaluation of Motorcycle Crash Injury Severities by Using Multinomial Models. Transportation Research Board Annual Meeting, Washington DC, 2006.

Synopsis 29: Interchange deficiencies - Acceleration/Deceleration lane length

1 Summary

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September 2016

COLOUR CODE: GREY

Explanation: The effect of acceleration and deceleration lane length on road safety is unclear and needs further investigation. The main reason is that mixed effects appear to exist in literature. Firstly, the influence on the number of crashes is unclear as studies show inconsistent findings. On the other hand, it is suggested that increased length of deceleration lanes results in lower crash severity (less severe crashes). However the impact of acceleration lanes has not investigated yet.

KEYWORDS

Acceleration lane; deceleration lane; length; interchanges

1.1 ABSTRACT

Overall, acceleration and deceleration lane lengths were found to have inconsistent and mixed influence on road safety. It is noted that the majority of studies focus on deceleration lanes on freeway exit areas. The majority of relevant literature investigates the number of crashes, suggesting that the effect is not clear. Nevertheless, most of recent studies indicate that increased deceleration lane length leads to more crashes (although less severe). The meta-analysis that was carried out confirmed the inconsistent findings as a non-significant effect of the overall estimate of deceleration lane length was found at a 95% level. Furthermore, it was also attempted to perform a meta-analysis on the basis of two studies examining the impact of deceleration lane length on crash severity, suggesting a non-significant effect. However, due to the fact that only two studies were included in this meta-analysis the results should be interpreted with care. Concluding, the inconsistent findings of international literature clearly suggests that further research is need on this topic.

1.2 BACKGROUND

1.2.1 Definitions of acceleration and deceleration lane length

Acceleration and deceleration lanes could be defined as "speed-change lanes", but usually, there is a clear distinction between acceleration and deceleration lanes. Most existing literature has a focused on deceleration lanes on freeway exit areas. Although this risk factor is defined as numerical variable, various different units have been assigned (e.g. feet, km, miles etc.). Furthermore, one study examined it as the logarithm of deceleration lane and one study examined it as a discrete parameter.

1.2.2 How does acceleration and deceleration lane length affect road safety?

It is expected that acceleration and deceleration lanes could more risky than the freeway mainline section (FHWA, 2010). When traffic approaches the freeway diverge areas, exiting vehicles need to diverge to the deceleration lanes in order to exit the freeway mainlines. Similarly, when traffic enters the freeway mainline areas, entering vehicles have to accelerate in order to meet the operating speed of the freeway. Therefore, in order to meet traffic safety and operation requirements, it is important that acceleration and deceleration lanes have the appropriate length so that entering and exiting vehicles complete sequential manoeuvres.

1.2.3 Which safety outcomes are affected by acceleration and deceleration lane length?

In international literature, the effect of acceleration and deceleration lane length on road safety has been mainly investigated on the basis of crash frequency (number of crashes occurred). Less frequently, deceleration lane length was found to affect crash severity (no injury, possible injury, non-incapacitating injury, incapacitating injury, fatality).

1.2.4 How is the effect of acceleration and deceleration lane studied?

In general, when an acceleration and deceleration lane is examined, crash data from police records are utilized to study their impact on outcome indicators. Regarding the methods of analysis, the effect of acceleration and deceleration lane is usually examined by applying multivariate linear statistical models. When crash frequency is examined, the relationship between lane length and number of crashes is consistently investigated by applying negative binomial models. However, less sophisticated methods have been applied as well, in order to show correlations between acc/dec lane lengths and crashes (Pearson correlation coefficient). On the other hand, crash severity is typically examined by applying ordered probit models.

1.3 OVERVIEW OF RESULTS

The initial examination of relevant studies suggests that a) the main focus is on deceleration lane length and b) that its effect on road safety is inconsistent. Although the effect of deceleration lane length on the number of crashes is not clear, recent studies tend to indicate that longer deceleration lanes are associated with more crashes. Regarding crash severity, the relevant studies consistently (Wang et al., 2009 and 2011) show that in shorter lane lengths more severe crashes tend to occur. Most of coded studies are from US states and Canada. Only one European study was found, specifically German Autobahns. Aside from Europe and USA, only China has been examined. On the other hand, little is known about various road users as the number of total crashes is investigated and transferability is not certain. Moreover, a few studies examine the frequency of fatal, injury and property damage crashes separately.

Research on the effect of lane length on crash numbers, includes similar modelling approaches (appropriate models for count data) and entered similar variables in the models (traffic, other geometrical elements etc.). The same statistical models were selected, namely negative binomial models. The vast majority considered fixed effects specification. Crash severity was rarely investigated, but the exact same outcome (5-scale severity scale) and the same method of analysis (ordered probit model) was chosen. Potential transferability of results is questionable, due to inconsistent findings of studies and because studies on crash severity were few. Moreover, studies on acceleration lane lengths were scarce and not recent. On the other hand, more research has been carried out on deceleration lane length effects, but transferability is uncertain since ramp types and other geometrical characteristics (number of exit lanes) were not the same.

Two separate meta-analyses were performed; one for crash frequency and one for crash severity. The estimate of the beta coefficient was 0.2156 (p-value = 0.3701) for acc/dec lane length when crash frequency is considered. The respective estimate of deceleration lane length when crash severity is considered was found to be -1.9383 (p-value = 0.2647).

1.4 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and methodologically sound. The only potential bias indicated in some of the studies, is the fact that the applied statistical methods and model specifications (fixed effects negative binomial models and ordered probit models) do not account for unobserved heterogeneity[1] that is possibly present. That happens because they assume the effect of the speed-change lane length on frequency (or severity) of crashes is constrained to be the same for all observations (freeway diverge areas). Consequently, the resulting parameter estimates may be biased. There are no studies focusing on the effect of acceleration lane length on crash or injury severity and only a few on crash frequency. Moreover, most of studies use data from US States, with specific focus on Florida State. It is noted that different road users are not considered. However, Wang et al. (2011) studied truck-related crashes. Summing up, data concerning more countries (especially European) and different road users are needed.

[1] For more details the reader is encouraged to refer to Karlaftis and Tarko (1998) and Washington et al. (2010).

2 Scientific overview

2.1 LITERATURE REVIEW

Highway interchanges are systems of minor roadways designed to connect two or more major roadways. Ramps are connected to mainline freeways by speed-change lanes that allow entering and exiting vehicles to speed up (acceleration lane) or slow down (deceleration lane) without conflicting with ongoing traffic on the freeway mainline areas. Figure 1 illustrates the distinction between ramps and their adjacent speed-change lanes.

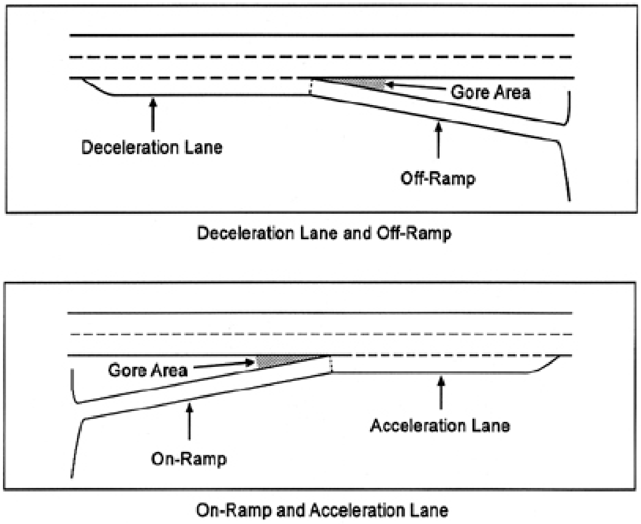


Figure 1 Illustration of speed-change lanes on interchanges. Source: Bauer and Harwood, 1998.

In order to meet traffic safety and operation requirements, it is important that acceleration and deceleration lanes have the appropriate length so that entering and exiting vehicles complete sequential manoeuvres. Early literature indicated that increased lengths of deceleration lanes would reduce crashes (Bared et al., 1998; Cirillo, 1970; Lundy, 1967). Nevertheless, more recent research on this topic indicates the opposite effect (Chen et al., 2009 and 2011; Garnowski and Manner, 2011). Another study conducted by Garcia and Romero (2006) found that long deceleration lanes would encourage drivers to further accelerate before they exit the freeway. However, mixed or non-significant findings still exist in recent studies (Cheng et al., 2012; Wu et al., 2014). Thus, the overall impact on safety is unclear.

Although speed-change lanes are usually defined as numerical variables, various different units have been assigned (e.g. feet, km, miles etc.). In addition, one study examined it as the logarithm of deceleration lane and one study examined it as a discrete parameter. The influence of acceleration and deceleration lane length on road safety has been mainly investigated on the basis of crash frequency (number of crashes occurred), but the vast majority of studies concern deceleration lanes. The influence of deceleration lane length on crash severity (no injury, possible injury, non-incapacitating injury, incapacitating injury, fatality) has also been studied, but rarely (Wang et al. 2009 and 2011). No studies investigating the probability of crash occurrence have been identified.

It is obvious that the main focus of international literature has been on deceleration lane length. Acceleration lane length has not received adequate attention by recent studies. More research on this topic is needed, as the issue of contradictory findings in literature has been recognized (Chen et al., 2014) and needs to be addressed on the basis of more studies with various designs, methods and sampling frames.

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

10 studies of sufficient quality were selected to be coded. 8 of them focused on the number of crashes (Bared, 1999; Bauer and Harwood, 1998; Chen et al., 2009; Chen et al., 2011; Cheng et al., 2012; Garnowski and Manner, 2011; Sarhan et al., 2008; Wu et al., 2014) and 2 on severity of crashes, once an crash has occurred (Wang et al., 2009 and 2011). No studies focusing on the direct relationship between probability of crash occurrence and deceleration/acceleration lane length were found.

The geographical location of most coded studies were a State in the US. Four studies (Chen et al., 2009 and 2011; Wang et al. 2009 and 2011) examine interchanges in the State of Florida. On the other hand, one study was carried out in Canada (Sarhan et al., 2008), one in German Autobahns (Garnowski and Manner, 2011) and one in China (Cheng et al., 2012). Therefore, there is overrepresentation of US studies.

Little is known about various road users as the number of total crashes of road users is investigated. However, one study focused on truck-related crashes (Wang et al., 2011). A remark is that ramp types and other geometrical characteristics of study designs in literature are not always the same (e.g. various ramp types, one-lane exits, two-lane exits etc.) and therefore transferability of results is questionable.

Usually, speed-change lane lengths are measured directly in km, m, miles or feet and no other transformations took place except for the study by Chen et al. (2009) that used the logarithm deceleration length (Chen et al., 2009).

Most of studies that examine the effect of deceleration lane length on the number of crashes, consider the total number of crashes. A number studies though examine the frequency of fatal, injury and property damage crashes separately (Bared, 1999; Bauer and Harwood, 1998; Wu et al., 2014). Crash severity was not investigated in many studies, but the same outcome indicator (5-scale severity scale) was chosen in the two relevant studies (Wang et al., 2009 and 2011).

In order to examine the underlying relationships between speed-change lanes and outcome indicators, studies deployed appropriate multivariable statistical models. However, not all studies used models but relied on more simple methods instead (Cheng et al., 2012). Most studies deployed straightforward statistical models (e.g. fixed effects negative binomial model, ordered probit model). It is noted that a number studies however, do not report standard errors (Bared, 1999; Bauer and Harwood, 1998; Sarhan et al., 2008) and could not therefore considered for further analysis. On the other hand, Wu et al., (2014) deployed Generalized estimating equations with temporal correlation to find the relationship between deceleration lane length and number of fatal crashes.
In general, the coded studies are of sufficient quality and methodologically sound. One potential bias indicated in some of the studies, is that they do not account for unobserved heterogeneity that is possibly present. This is because the model specifications (fixed effects negative binomial models

and ordered probit models) assume that the effect of the explanatory variable on road safety is constrained to be the same for all observations (freeway diverge areas). Consequently, the resulting parameter estimates may be biased. Other restrictions and biases could also exist. Further information can be found in Lord and Mannering (2010) and Savolainen et al. (2011). Table 1 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 1 Description of coded studies

Author(s), Year	Sample and study design	Method of analysis	Unit of analysis	Outcome indicator	Main result
Sarhan et al., 2008	26 interchanges along Highway 417 within the City of Ottawa, Canada for the period 1998-2002	Fixed effects negative binomial models	Acceleration and deceleration lane length (separately) in meters	Crash frequency (number of crashes)	Increased acceleration and deceleration lane lengths leads to reduced number of crashes
Bared, 1999	1452 crashes in Intestates in Washington State, US., for the period 1993-1995	Fixed effects negative binomial models	Acc/dec lane length in miles	Crash frequency (number of fatal, injury and total crashes)	Increased acceleration and deceleration lane lengths leads to reduced number of crashes (at 90% level only)
Bauer and Harwood, 1998	13706 total crashes in 2000 ramps in Interstates at Washington State, US, for the period 1993-1995	Fixed effects negative binomial models	Acc/dec lane length in miles	Crash frequency (number of fatal, injury and total crashes)	Mixed effects of the effect of acceleration and deceleration lane lengths
Chen et al., 2009	7872 crashes at 424 freeway segments in the State of Florida, US, for the period 2004-2006.	Fixed effects negative binomial models	Logarithm of deceleration lane length in miles	Crash frequency (number of crashes)	Increased deceleration lane lengths leads to increased number of crashes
Chen et al., 2011	Crashes in 74 freeway segments in the State of Florida, US, for the period 2004-2006	Fixed effects negative binomial models	Deceleration lane length in kilometres	Crash frequency (number of crashes)	Increased deceleration lane lengths leads to increased number of crashes
Cheng et al., 2012	7013 crashes on a 200km freeway in China, between 2006 and 2008.	Pearson correlation coefficient	Acc/dec lane length in kilometers	Crash frequency (number of fatal crashes)	Mixed effects of the effect of acceleration and deceleration lane lengths
Garnowski and Manner, 2011	3048 crashes in 197 ramps, between 2003 and 2005) in Autobahns in Germany.	Fixed effects negative binomial models	Deceleration lane length (lower or higher than 180 meters)	Crash frequency (number of fatal crashes)	Deceleration lane lengths higher 180 meters are associated with increased number of fatal crashes
Wang et al., 2009	10946 crashes in Florida state, US for the period 2003-2006	Ordered probit models	Deceleration lane length in feet	Crash injury severity* (5-point scale)	Increased length of deceleration lanes reduces crash injury severity
Wang et al., 2011	4630 crashes in 391 freeway diverge segments in Florida state, US, for 2005-2008	Ordered probit models	Deceleration lane length in miles	Crash injury severity* (5-point scale)	Increased length of deceleration lanes reduces crash injury severity
Wu et al., 2014	4429 crashes in 32 segments in Guangshen freeway in China for the period 2006-2009.	Generalized estimating equations with temporal correlation	Deceleration lane length in kilometres	Crash frequency (number of fatal crashes)	Non-significant effect of deceleration lane length on the number of fatal crashes

* 1: no injury, 2: possible injury, 3: non incapacitating injury, 4: incapacitating injury, 5: fatal

2.3 ANALYSIS METHODS AND RESULTS

2.3.1 Introduction

After applying the appropriate transformations, it was decided to carry out 2 separate random-effects meta-analyses in order to find a) the overall estimate of deceleration lane length on crash frequency and b) on crash severity respectively. In each meta-analysis, only studies which have similar design, outcome indicator and same model specification (i.e. fixed effects negative binomial models) were considered for further analysis. Studies not reporting standard errors were not included in the meta-analyses. The former meta-analysis revealed the estimate of the beta coefficient of deceleration lane length in the negative binomial model form, whilst the latter revealed the estimate of the beta coefficient of deceleration lane length in the ordered probit model form.

The reasons for the decision to carry out meta-analyses are:

a) A minimum required number of effects is achieved (3)
b) Studies that were considered used the same model specification (e.g. fixed effects negative binomial model, ordered probit model)
c) The sampling frames were similar
d) Outcome indicators of studies in each meta-analysis were the same.

Studies not reporting standard errors were not included in the meta-analyses. Although only 2 studies were identified for the estimate of deceleration lane length on crash severity, it was decided to carry out a meta-analysis following the recent study of Roshandel et al. (2015) in Crash Analysis and Prevention journal.

2.3.2 Overall estimate for crash frequency

Results of the random-effects meta-analysis indicate that the overall estimate of the effect of deceleration lane length on crash frequency (in Km) is 0.2156, while the 95% confidence intervals are -0.2558 and 0.6869 respectively (Table 2). The p-value (0.3701) indicates a non-significant effect. Therefore, deceleration lane length does not significantly affect the number of crashes. Figure 2 illustrates the forest plot of the estimates.

Table 2 Random effects meta-analyses for deceleration lane length effects on crash frequency.

Variable	Unit	Estimate	Std. Error	p-value	95% CI
Dec.lane	km	0.2156	0.2405	0.3701	(-0.2558, 0.6869)

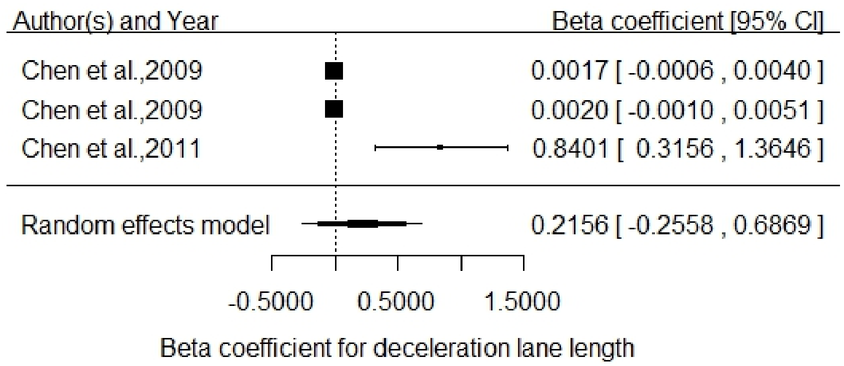


Figure 2 Forest plot of the effect of deceleration lane length (in km) on crash frequency.

Heterogeneity

The Q test is significant (Q= 9.838, p-value = 0.0073) suggesting that considerable heterogeneity exists among the true effects.

Publication Bias

A funnel plot (Figure 3) was firstly produced in order to detect potential publication bias. No publication bias seem to exist. The regression test for funnel plot asymmetry was not significant at a 95% level (p-value = 0.0892), suggesting no strong existence of publication bias.

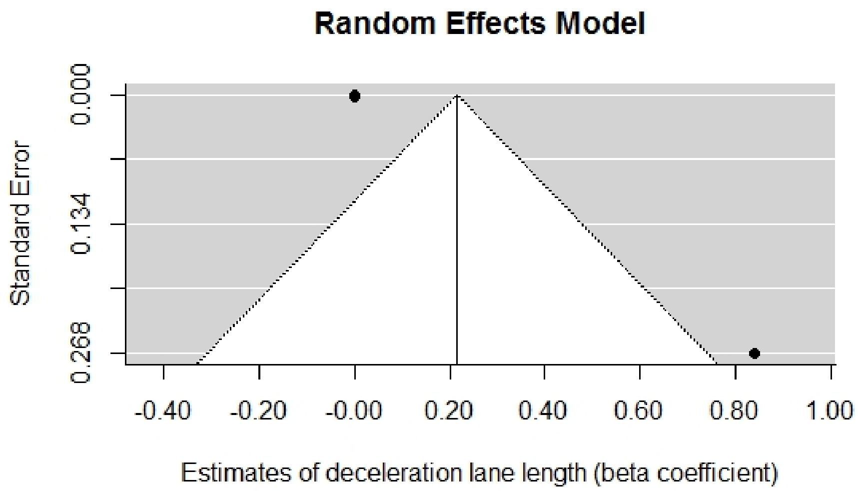


Figure 3 Funnel Plot for crash frequency (effect of deceleration lane length).

2.3.3 Overall estimate for crash severity

Results of the random-effects meta-analysis indicate that the overall estimate of the effect of deceleration lane length on crash severity (in Km) is -1.9383, while the 95% confidence intervals are -5.3446, 1.4680 respectively (Table 3). The p-value (0.2647) indicates a non-significant effect. Thus, deceleration lane length does not have any impact on crash severity. Figure 4 illustrates the forest plot of the estimates.

Table 3 Random effects meta-analyses for deceleration lane length effects on crash severity.

Variable	Unit	Estimate	Std. Error	p-value	95% CI
Dec.lane	km	-1.9383	1.7380	0.2647	(-5.3446, 1.4680)

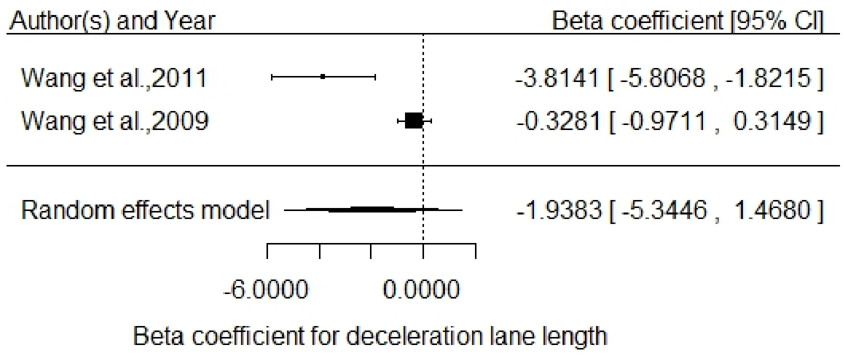


Figure 4 Forest plot of the effect of deceleration lane length (in km) on crash severity.

Heterogeneity

The Q test is significant (Q= 10.6481, p-value = 0.0011) suggesting that considerable heterogeneity exists among the true effects.

Publication Bias

A funnel plot (Figure 5) was firstly produced in order to detect potential publication bias. No publication bias seem to exist. Due to low number of available studies this could not be further tested.

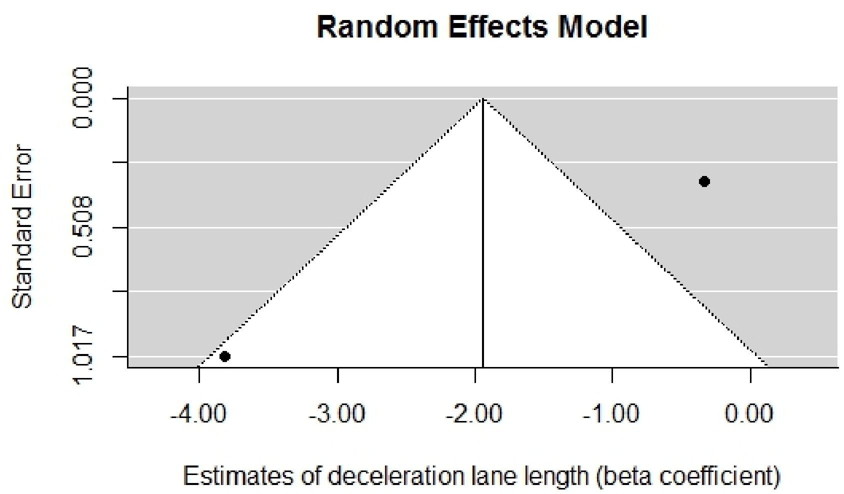


Figure 5 Funnel Plot for crash severity (effect of deceleration lane length).

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The search strategy aimed at identifying the best quality and recent studies to estimate the effect of this risk factor. In general, only recent journal studies in English language (after 1990) in the field of Engineering were considered, from the Scopus database. After an abstract and title screening, out of 137 potentially eligible studies, 15 were found to be mostly relevant to the topic. However, after a full-text screening 10 quality studies were coded and included in the synopsis.

Table 4 Literature search strategy. 23rd March 2016

search no.	search terms / operators / combined queries	hits
#1	(„acceleration lane " OR „ deceleration lane")	1,635
#2	(„acceleration lane length" OR „ deceleration length")	208
#3	(„casualties" OR „fatalities" OR „traffic safety" OR „crash" OR „crash risk" OR „severity" OR „frequency" OR „collision" OR „incident" OR „accident")	22,319
#4	#1 AND #3	378
#5	#2 AND #3	54
#6	#1 OR #2 AND #3	**137**

The final 10 studies included in the synopsis indicate that the topic has not been thoroughly investigated. The 10 of highest quality studies out of 15 were coded according to the following prioritizing criteria:

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

No "grey" literature was examined. No meta-analyses were found. However, one very informative and of high quality report was chosen to be coded and included in the synopsis (Bauer and Harwood, 1998).

3.2 SUMMARY OF FINDINGS

Table 4 Summary of results of the coded studies.

#	Author(s), Year	Outcome indicator	Quantitative estimate	Effect on road safety risk
1	Sarhan et al., 2008	Crash frequency [number of crashes]	Deceleration lane length for all segments: beta coefficient=-0.0015	↓
			Deceleration lane length for weaving segments: beta coefficient=-0.0016	↓

			Acceleration lane length for all segments: beta coefficient=-0.002	↓
			Acceleration lane length for weaving segments: beta coefficient=-0.0014	↓
2	Bared, 1999	Crash frequency [number of crashes]	Acceleration/deceleration lane length: beta coefficient=-0.0014	↓
3	Bauer and Harwood, 1998	Crash frequency [number of crashes]	Acceleration/deceleration lane length for fatal and injury crashes: beta coefficient=-4.45, CI[90%]=[-7.21,-1.91]	↓
4	Chen et al., 2009	Crash frequency [number of crashes]	Logarithm of deceleration lane length for one-lane exit ramps: beta coefficient=0.2345, p-value=<0.001	↑
			Logarithm of deceleration lane length for two-lane exit ramps: beta coefficient=0.3065, p-value=0.0873	↑
5	Chen et al., 2011	Crash frequency [number of crashes]	Deceleration lane length for one-lane exit ramps: beta coefficient=-0.7575, p-value=0.0011	↓
6	Cheng et al., 2012	Crash frequency [number of total, fatal, incapacitating,non-incapacitating, no injury crashes]	Left-turn acceleration lane from crossroad to mainline freeway - Fatal crashes: correlation coefficient=-0.58, p-value=0.066	↓
			Left-turn acceleration lane from crossroad to mainline freeway - Incapacitating crashes: correlation coefficient=-0.1240, p-value=0.385	-
			Left-turn acceleration lane from crossroad to mainline freeway - Non-incapacitating crashes: correlation coefficient=-0.16, p-value=0.3530	-
			Left-turn acceleration lane from crossroad to mainline freeway - No injury crashes: correlation coefficient=0.5210, p-value=0.093	↑
			Left-turn acceleration lane from crossroad to mainline freeway - Total crashes: correlation coefficient=0.417, p-value=0.152	-
			Left-turn deceleration lane from mainline freeway to crossroad- fatal crashes: correlation coefficient=0.031, p-value=0.471	-
			Left-turn deceleration lane from mainline freeway to crossroad- Incapacitating crashes:correlation coefficient=-0.262, p-value= 0.266	-
			Left-turn deceleration lane from mainline freeway to crossroad- Non-capacitating crashes correlation coefficient=0.188, p-value= 0.328	-
			Left-turn deceleration lane from mainline freeway to crossroad-No injury crashes correlation coefficient=0.0545, p-value=0.081	↑
			Left-turn deceleration lane from mainline freeway to crossroad- Total crashes correlation coefficient=0.5050, p-value=0.1010	-
			Right-turn acceleration lane from crossroad to mainline freeway - Fatal crashes: correlation coefficient=0.149, p-value=0.363	-
			Right-turn acceleration lane from crossroad to mainline freeway - Incapacitating crashes: correlation coefficient=-0.284, p-value=0.248	-
			Right-turn acceleration lane from crossroad to mainline freeway - Non-capacitating crashes: correlation coefficient=0.191, p-	-

			value=0.325	
			Right-turn acceleration lane from crossroad to mainline freeway - No injury crashes: correlation coefficient=0.424, p-value=0.148	-
			Right-turn acceleration lane from crossroad to mainline freeway - Total crashes: correlation coefficient=0.48, p-value=0.114	-
			Right-turn deceleration lane from mainline freeway to crossroad - Fatal crashes: correlation coefficient=0.145, p-value=0.366	-
			Right-turn deceleration lane from mainline freeway to crossroad - Incapacitating crashes: correlation coefficient=-0.39, p-value=0.17	-
			Right-turn deceleration lane from mainline freeway to crossroad - Non-incapacitating crashes: correlation coefficient=-0.276, p-value=0.254	-
			Right-turn deceleration lane from mainline freeway to crossroad - No injury crashes: correlation coefficient=0.506, p-value=0.1010	-
			Right-turn deceleration lane from mainline freeway to crossroad - Total crashes: correlation coefficient=0.48, p-value=0.114	-
7	Garnowski and Manner, 2011	Crash frequency [number of crashes]	Deceleration lane length>180m: beta coefficient=0.4352, standard error=0.1382	↑
8	Wang et al., 2009	Crash severity[no injury, possible/visible injury, no-incapacitating injury, incapacitating injury, fatal]	Deceleration lane length: beta coefficient=-0.0001, p-value=0.075	↓
9	Wang et al., 2011	Crash severity[no injury, possible/visible injury, no-incapacitating injury, incapacitating injury, fatal]	Deceleration lane length: beta coefficient=-2.3838, p-value=0.000	↓
10	Wu et al., 2014	Crash frequency [number of crashes]	Not retained in the final model	-

3.3 LIST OF STUDIES

3.3.1 List of coded studies

A detailed list of studies coded is provided below:

1) Bared J., Giering G., Warren D. (1999). Safety Evaluation of Acceleration and Deceleration Lane Lengths, ITE Journal, May 1999.

2) Bauer K.M., Harwood D.W. (1998). Statistical models of accidents on interchange ramps and speed-change lanes. Report No. FHWA-RD-97-106, 1998.

3) Chen H., Liu P., Lu J.J., Behzadi B. (2009). Evaluating the safety impacts of the number and arrangement of lanes on freeway exit ramps. Accident Analysis and Prevention 41, 543-551. doi: 10.1016/j.aap.2009.01.016.

4) Chen H., Zhou H., Zhao J., Hsu P. (2011). Safety performance evaluation of left-side off-ramps at freeway diverge areas. Accident Analysis and Prevention 43, 605-612. doi: 10.1016/j.aap.2010.08.019.

5) Cheng Y., Chen F., Noyce D.A., Huang X. (2012). The impact of interchange configuration on rural-eight lane freeways, TRB 2012 Annual Meeting, Washington DC.
6) Garnowski, M., & Manner, H. (2011). On factors related to car accidents on German Autobahn connectors. Accident Analysis and Prevention, 43(5), 1864-1871. doi:10.1016/j.aap.2011.04.026.
7) Sarhar M., Hassan Y., El Halim A.O.A. (2008). Safety Performance of Freeway Sections and Relation to Length of Speed Change Lanes. Canadian Journal of Civil Engineering 35(5), 531-541.
8) Wang Z., Cao B., Deng W., Lu J., Zhang Z. (2011). Safety Evaluation of Truck-Related Crashes at Freeway Diverge Areas, 2011 TRB Annual Meeting, Washington DC.
9) Wang Z., Chen H., Jian J. (2009). Exploring Impacts of Factors Contributing to Injury Severity at Freeway Diverge Areas, TRB 2009 Annual Meeting, Washington DC.
10) Wu W. Q., Wang W., Li Z. B., Liu P., Wang, Y. (2014). Application of generalized estimating equations for crash frequency modeling with temporal correlation. Journal of Zhejiang University-Science A, 7(15), 529-539. doi: 10.1631/jzus.A1300342.

Other references

1) Chen H., Zhou H., Lin P.-S. (2014). Freeway deceleration lane lengths effects on traffic safety and operation. Safety Science 64, 39–49. doi: http://dx.doi.org/10.1016/j.ssci.2013.11.007.
2) Cirillo J.A. (1970). The Relationship of Accidents to Length of Speed-Change Lanes and Weaving Areas on Interstate Highways. Highway Research Record (HRR) Report HRR 312.
3) Federal Highway Administration (FHWA). (2010). 2010 Status of the Nation's Highways, Bridges, and Transit: Conditions & Performance. U.S. Department of Transportation. doi: http://www.fhwa.dot.gov/policy/2010cpr/.
4) Garcia A., Romero A.R. (2006). Experimental observation of vehicle evolution on a deceleration lane with different lengths. 85th Transportation Research Board Annual Meeting, Washington, DC.
5) Karlaftis M.G., Tarko, A. (1998). Heterogeneity considerations in accident modeling. Accident Analysis and Prevention 30 (4), 425–433.
6) Lord D., Mannering F. (2010). The Statistical Analysis of Crash-Frequency Data: A Review and Assessment of Methodological Alternatives. Transportation Research Part A, 44(5), 291-305 · June 2010. doi: 10.1016/j.tra.2010.02.001.
7) Lundy R.A. (1967). The Effect of Ramp Type and Geometry on Accidents. Highway Research Record (HRR), 163, 80–119.
8) Roshandel S., Zheng Z., Washington S. (2015). Impact of real-time traffic characteristics on freeway crash occurrence: systematic review and meta-analysis. Accident Analysis and Prevention, 79, 198-211.
9) Savolainen P.T., Mannering F.L., Lord D., Quddus M.A. (2011). The statistical analysis of highway crash-injury severities: a review and assessment of methodological alternatives. Accident Analysis and Prevention, 43(5), 1666-76. doi: 10.1016/j.aap.2011.03.025.
10) Washington S.P., Karlaftis M.G., Mannering F.L. (2010). Statistical and econometric methods for transportation data analysis. Chapman & Hall/CRC.

Synopsis 30: At-grade junctions deficiencies - Number of conflict points

1 Summary

Soteropoulos, A. & Stadlbauer, S., September 2016

1.1 COLOUR CODE: YELLOW

The number of conflict points at junctions, which is mostly expressed through the (total) number of lanes – appears to have a negative effect on road safety. However some studies – especially for specific crash types – show different effects. Thus, whereas a higher number of conflict points tends to increase crash risk in general, it might be that for specific crash types an additional lane and with it an addition of conflict points could nevertheless probably reduce crash risk.

1.2 KEYWORDS

Number of conflict points; junction; number of lanes

1.3 ABSTRACT

The number of conflict points at junctions, which is mostly expressed through the (total) number of lanes – appears to deteriorate road safety. Studies on accident frequency mostly indicate that an increase of the number of lanes and therefore an increase in the number of conflict points tends to increase crash frequency or that junctions with less lanes (and therefore less conflict points) tend to have lower numbers of crashes in general. Furthermore some studies show this tendency for specific types of lanes (e.g. number of left-turn lanes in right-driving countries) as well as for specific crash types (e.g. angle-crashes). However some studies – especially for specific crash types (e.g. rear-end crashes) – show different effects. Summarizing, in general it appears that an increase of the number of conflict points tend to increase crash frequency, however for some crash types (e.g. rear-end crashes) an additional lane which is connected with additional conflict points could nevertheless probably reduce crash risk.

1.4 BACKGROUND

1.4.1 What is the number of conflict points?

Conflict points occur at junctions as result of two or more approaching traffic streams. Whether two traffic streams join, cross or divide, potential for conflict can arise (Wadwha and Thomson 2006). The location, where this potential conflict e.g. due to road users approaching each other without taking an action like braking or steering arises, is the conflict point (Dijkstra and Van Petegem 2015). The number of conflict points at intersections is related to the number of conflicting traffic flow movements respectively directions at the intersection (Eccles and Levinson 2007). It mainly depends on the intersections' configuration and control (Wadwha and Thomson 2006). The number of conflict points increases substantially as the number of legs increase (Eccles and Levinson 2007). A three-leg junction for example has 9 conflict points between the streams of traffic passing through the junction, whereas a four-leg junction has 32 conflict points between the streams of traffic (Elvik et al. 2009). Thus conflict points are related to the amount of possible traffic streams (straight, left-turn, right-turn) but also to the number of lanes (single-lane, multi-lane).

1.4.2 How does the number of conflict points affect road safety?

In general a higher number of conflict points is associated with a higher possibility of potential conflicts between the streams of traffic passing through the junction. These conflicts differ depending on whether two traffic streams join, cross or divide and result in different crash types. When traffic is transferring from one stream into another, merging conflicts may arise, resulting in sideswiping and rear ending crashes (at relative low speed). Traffic streams intersecting through other traffic streams create crossing conflicts, resulting in right angle and head-on crashes (often at relative high speed). When traffic is separating itself from an existing traffic stream diverging conflicts arise, resulting in rear-end crashes (often at relative low speed). Furthermore at multi-lane sections/intersections of roads, weaving manoeuvres can cause conflicts, resulting in rear ending and sideswiping crashes (Wadwha and Thomson 2006). However some studies also show a lower accident frequency for specific crash types like rear-end crashes with an increase in the number of lanes (Wang et al. 1999).

1.4.3 Which safety outcomes are affected by number of conflict points?

In the international literature, the effect of the number of conflict points on road safety has been measured mainly on one basic outcome, namely accident frequency (number of crashes occurred). Only one study focusing on accident severity (severity of injuries of occupants given that an accident has occurred) was found.

1.4.4 How is the effect of number of conflict points studied?

International literature indicated that the effect of the number of conflict points on road safety is usually examined by applying multivariable linear statistical models. In the most commonly found accident frequency models, the relationship between number of conflict points – mostly expressed through the (total) number of (right- or left-turn) lanes – and number of crashes is investigated mostly with negative binomial or Poisson models. In the one study focusing on accident severity, a binary probit model was applied. Moreover one study only undertook a crash data analysis and calculated fatality rates for different intersection types and controls. The studies identified focused on intersections at urban roads. Most research has been done in the United States and Japan; no European study was found.

1.5 OVERVIEW RESULTS

Regarding the effects of the number of conflict points on road safety, it appears that an increase of the number of conflict points tends to increase crash frequency. Most studies on accident frequency indicate that an increase of the number of lanes – effects of the number of conflict points were analysed mostly through effects of the (total) number of (right-, left-turn or through) lanes – and therefore an increase in the number of conflict points tend to increase crash frequency or that intersections with less lanes (and therefore less conflict points) tend to have lower numbers of crashes in general. Furthermore some studies show this tendency for specific types of lanes (e.g. number of left-turn lanes in right-driving countries) and specific crash types (e.g. angle-crashes). Some studies – especially for specific crash types – however also show different effects. Thus in general it appears that an increase of the number of conflict points/number of lanes tend to increase crash frequency, however it might be that for some crash types an additional lane which is connected with an addition of conflict points could nevertheless probably reduce crash risk.

1.6 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound. However some of the studies used only small samples for investigation and in the study of Wang et al. 2014 actual daily turning movements were not obtained. Furthermore it must be emphasized that the number of conflict points were mostly expressed through the (total) number of (right-, left-turn or through) lanes. In none of the studies which deployed statistical models the actual number of conflict points was used as a variable in the models. Only one study undertook a crash data analysis and calculated fatality rates for different intersection types and therefore for an actual specific number of conflict points.

Overall, the topic has been very deeply studied (number of relevant studies is 13). It is interesting that most of the studies focus on accident frequency rather than accident severity. Studies often focused on motor-vehicle crashes and sometimes only on specific crash types. Moreover research was mostly carried out in the United States and is probably linked with national specifications.

2 Scientific overview

2.1 RESULTS

In the studies identified effects of the number of conflict points on road safety were analysed mainly using accident frequency models and the effects for the number of conflict points were mostly expressed through the (total) number of (right-, left-turn or through) lanes. Regardless of the number of lanes, cross roads have more conflict points than T-junctions and roundabouts (see synopsis on junction type for details).

Most studies on accident frequency indicate that an increase in the number of lanes, and therefore an increase in the number of conflict points tend to increase crash frequency, however often effects for specific types of lanes (e.g. left-turn lane) as well as for specific crash types (e.g. angle-crashes) are presented as well.

Results of Abdel-Aty et al. (2006) for example indicate that the total number of lanes of the intersection (intersection size) was positively associated with crash frequency: crash frequency significantly increased as the number of lanes increased. Moreover the presence of exclusive right-turn lanes on major and minor roadways reduced intersection crash occurrence significantly. Furthermore Qin et al. (2010) indicate that compared to 4-lane intersections (more conflict points), 2-lane intersections tend to have lower number of crashes (significant effects).

For motorcycle crashes, results of Haque et al. (2010) indicate that the number of lanes along the major roadway and with it the number of conflict points of four-legged signalized intersections is significantly associated with motorcycle crashes: an additional lane in the major roadway increased the motorcycle crashes by about 13%, an additional lane in the minor roadway increased the motorcycle crashes by about 19%. For signalized T-intersections the latter increased the motorcycle crashes by about 73% (significant positive association between number of lanes on minor roadway and motorcycle crashes).

In addition Abdel-Aty et al. (2011) indicate that compared with 2x2 lanes (minor x major road) and 2x3 lanes four-legged intersections, 3x2 lanes, 3x3 lanes, 3x4 lanes, 3x5 lanes, 3x6 lanes and 3x8 lanes four-legged intersections significantly increase angle crash frequency. However for other intersections (e.g. 4 lanes on minor road) no significant effects were found.

Results of Dong et al. (2014a) – focussing on car, car-truck and truck accident frequency – indicate that an increase in the number of right-turn lanes (on major and minor road) was associated with a significantly increase in car crash frequencies (supposedly rear-end crashes), however no significant association was found for car-truck and truck crashes. Instead an increase in the number of left-turn lanes on the major road significantly increased car-truck and truck crash frequencies (supposedly sideswipe and angle crashes), whereas no significant association was found for car crashes.

Dong et al. (2014b) indicate – also focussing on car, car-truck and truck accident frequency – that the number of left-turn lanes on major and minor road significantly increases crash frequency for car, car-truck and truck-crashes (supposedly angle-crashes). This was also the case for the number of exclusive right-turn lanes on major and minor roads (supposedly rear-end crashes).

Wang and Nihan (2001) – focussing on crashes with crossing vehicles – indicate that the existence of more than two right-turn lanes was found to significantly increase accident risk (crashes with crossing vehicles).
Results of Wang and Nihan (2004) – focussing on collisions between bicycles and (left- or right-turning) motor vehicles – indicate a significant negative effect for the number of right-turn lanes as well as for the number of outgoing lanes on the left approach on crashes between bicycles and left-turning motor vehicles, resulting from the increase in the number of conflict points/conflicts: when there are more right-turn lanes at the opposing approach, conflicts between left-turning vehicles and opposing right-turning vehicles will increase at the merging section in the left approach, and such conflicts will consequently affect the left-turning drivers' ability to detect crossing bicyclists and similarly the number of outgoing lanes at the left approach heightens crash risk because of the increasing conflict points a bicyclist may face when crossing the left approach. Furthermore for crashes between bicycles and right-turning motor vehicles a significant negative effect for intersection approaches sheltered by elevated roadways as well as for the number of right-turn lanes on the entering approach was found.

Wang and Abdel-Aty (2008) – analysing collisions of left-turning vehicles with on-coming through traffic, with near-side crossing through traffic, with other left-turning vehicles and collisions of left-turning vehicles merging into the receiving lane of the far side approach – indicate that compared to 1 through lane on the opposing approach, 2 and 3 or more through lanes on the opposing approach significantly increased crash frequency of collisions between left-turning vehicles with on-coming through traffic.

Wang et al. (2014) analysed the impact of the number of through lanes, left-turn lanes and right-turn lanes on the entering approach plus the impact of the number of trough lanes on the opposing approach on accident frequency in general and the accident frequency of specific accident types in particular. Although results were not statistically significant, the number of left-turn lanes and the number of right-turn lanes on the entering approach was positively associated with accident frequency. For the number of right-turn lanes on the entering approach this was also the case for rear-end crash frequency. For sideswipe crashes the number of through lanes, the number of left-turn lanes and the number of right-turn lanes on the entering approach were positively associated with crash frequency. For the number of through lanes on the entering approach this was also the case for crashes with an oncoming vehicle on the opposing approach going left.

However some studies on accident frequency also show different effects, although often for specific crash types. Results of Wang et al. (1999) for example – focussing on rear-end crashes – indicate that the lane number of the entering approach significantly decreases rear-end crashes. However the authors relate this to the lower probability of pedestrians disregarding a red signal because of the higher crossing time. In their study on crashes with crossing vehicles, Wang and Nihan (2001) also indicate a significant positive effect of the number of through lanes on the entering approach on crashes with crossing vehicles, resulting from the fact that when there are more through lanes on the entering approach, right-turning vehicle drivers from the opposing approach tend to be more conservative as they know that it takes longer to complete the right-turn and the chance to find an acceptable gap is rare. Thus the probability of encountering an obstacle vehicle was significantly lower at intersections with approaches with more through lanes.

In addition Wang and Abdel-Aty (2008) – for collisions of left-turning vehicles with near-side crossing through traffic – indicate that compared to one through lane on the opposing approach, 2 or 3 through lanes on the opposing approach significantly decreased crash frequency, although effects for 4 or more through lanes on the opposing approach were not statistically significant. Moreover for collisions of left-turning vehicles with other left-turning vehicles it was found that compared to the approaches/intersections with no left-turn lanes, the approach with a single left-turn lane had significantly fewer crashes, although effects for approaches/intersections with double left-turn lanes were not statistically significant. In addition for collisions of left-turning vehicles merging into the receiving lane of the far side approach, it was found that compared with no through lanes on the opposing approach, 1 and 2 or more through lanes on the opposing approach (increased number of through lanes) decreased accident frequency significantly. This is – as described by the authors – because in these crashes the common contributing causes are "failed to yield right-of-way" and "disregarded traffic signal" and with increasing number of lanes and with it increasing crossing distance, drivers will be more aware of the signal and obey the traffic light. Furthermore Wang et al. (2014) – although results were not statistically significant – also indicate that the number of through lanes on the entering approach was negatively associated with crash frequency of right-angle crashes and that the number of through lanes on the opposing approach was negatively associated with crash frequency of crashes with approaching vehicles going left, hitting left-coming vehicles.

Results of the only study on accident severity – Haleem and Abdel-Aty (2010) – indicate that 1x2 lanes, 1x3 lanes and 1x4 lanes three-legged intersections (minor x major road) significantly increased the probability of severe injury compared to 4x2 lanes, 4x4 lanes, 4x6 lanes and 4x8 lanes intersections. The authors describe that this might be because the 1x2 lanes, 1x3 lanes and 1x4 lanes three-legged intersections could exist at ramp junctions with yield signs, were merging and diverging manoeuvres occur and hence traffic conflicts and serious injuries are likely especially at higher speeds. For other intersections (e.g. 2 lanes or 3 lanes on minor road) no significant effects were presented.

The one study which only undertook a crash analysis – Wadwha and Thomson (2006) – calculated fatality rates for different intersection types with respect to the number of conflict points, shows that the fatality rate heightens with an increase in the number of (crossing) conflict points. This was also the case for the proportion of crashes.

Table 1 illustrates the results of the vote-count analysis. Results show that a high number of conflict points tends to increase the accident frequency in general. However, when not investigated for a specific road network (e.g. urban roads) there might be different effects of a high number of conflict points or additional lanes. This might also be due to a rather small sample size.

Table 1 Results of the vote-count analysis

	Total number of effects tested	**Result (number of effects)**			**Result (% of effects)**	
		↗	-	↘	↗	↘
Accident Frequency	**60**	**30**	**20**	**10**	**75%**	**25%**
all	26	4	14	8	33%	67%
urban	34	26	6	2	93%	7%
rural	-	-	-	-	-	-
Accident Severity	**5**	**1**	**4**	**0**	**100%**	**0%**
all	5	1	4	0	100%	0%
urban	-	-	-	-	-	-
rural	-	-	-	-	-	-

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

Overall 13 high quality studies on the effects of number of conflict points on road safety were selected and coded. Most studies – 11 in total – focused on accident frequency, 1 study on accident severity and 1 study only undertook a crash data analysis. In order to examine the relationship between number of conflict points – mostly expressed through the (total) number of (right-, left-turn or through) lanes – and outcome indicators, studies on accident frequency and on accident severity deployed multivariable statistical models (i.e. negative binomial regression, binary probit model etc.) as a method of examining the topic and controlled for other geometrical characteristics and traffic flow as well.

Studies on accident frequency mainly deployed negative binomial models (Abdel-Aty and Wang 2006; Abdel-Aty and Haleem 2011; Dong et al. 2014a; Dong et al. 2014b; Haque et al. 2010; Qin et al. 2010; Wang et al. 1999; Wang and Nihan 2001; Wang and Nihan 2004; Wang and Abdel-Aty 2008; Wang et al. 2014) or Poisson models (Dong et al. 2014a; Haque et al. 2010). The study on accident severity (Haleem et al. 2010) deployed a binary probit model. The study which only undertook a crash data analysis (Wadwha and Thomson 2006) calculated fatality rates for different intersection types and controls with regard to the number of conflict points.

The studies identified mostly focused on intersections at urban roads. Most studies focused on motor-vehicle crashes and some of these studies focused on specific crash types (e.g. angle-crashes). Some other studies also focused on crashes of other road users/vehicle types (motorcycles, trucks, bicycles). Most research has been done in the United States (8 studies) and Japan (3 studies). But also Singapore (1 study) and Australia (1 study) were part of the examination.

Table 2 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 2 Description of coded studies

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Abdel-Aty, 2006, United States	Observational, negative binomial regression including 476 signalized intersections between 1999 and 2000	Regression analysis between intersection characteristics and crash occurrence	Intersections with different characteristics	-
Abdel-Aty, 2011, United States	Observational, negative binomial model, 2475 unsignalized intersections between 2003-2006	Regression analysis between intersection characteristics and crash occurrence	Intersections with specific size ("2x2" and "2x3")	Focus on angle crashes
Dong, 2014a, United States	Observational, case-control, unmatched, Poisson-lognormal regression model, 245 signalized intersections and 6790 crashes between 2005 and 2009	Regression analysis between intersection characteristics and crash occurrence	-	Road network was limited to urban roads, focus on crashes types

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Dong, 2014b, United States	Observational, case-control, unmatched , multivariate random-parameters zero-inflated negative binomial (MRZINB) regression model, 3015 intersections and 7840 crashes between 2001 and 2005	Regression analysis between intersection characteristics and crash occurrence	-	Road network was limited to urban roads, focus on crashes types
Haleem, 2010, United States	Observational, binary probit model, crash data of 2043 intersections between 2003 und 2006	Regression analysis between intersection characteristics and crash occurrence	Intersections with specific size ("4x2", "4x4", "4x6" and "4x8" intersections)	Focus on accident severity
Haque, 2010, Singapore	Observational, time-series, Cross-sectional, hierarchical Poisson model, 270 crossroads and 101 T-arms with 1080 and 404 observations between 2003 and 2006	Regression analysis between intersection characteristics and crash occurrence	-	Signalized intersections on urban road network
Qin, 2010, United States	Observational, quantile regression model, 1710 intersections between 2001 and 2003	Regression analysis between intersection characteristics and crash occurrence	4-lane intersections	-
Wadhwa, 2006, Australia	Crash data analysis of 2748 intersections, 1999-2002	-	-	Only fatal crashes
Wang, 1999, Japan	Observational, negative binomial model, 116 intersections with 1105 observations, 1992-1995	Regression analysis between intersection characteristics and crash occurrence	-	Road network was limited to urban roads, focus on rear-end crashes
Wang, 2001, Japan	Observational, negative binomial model, 81 signalized intersections,	Regression analysis between intersection characteristics and crash occurrence	-	Road network was limited to urban roads, focus on accident with crossing vehicle
Wang, 2004, Japan	Observational, negative binomial model, 115 signalized intersections, 1992-1995,	Regression analysis between intersection characteristics and crash occurrence	-	Road network was limited to urban roads
Wang, 2008, United States	Observational, generalized estimating equations (GEE) with a negative binomial model as link function, 197 signalized intersections with 13218 crashes, 2000-2005	Regression analysis between intersection characteristics and crash occurrence	1 through lane, no left-turn lane on entering approach	-
Wang, 2014, United States	Observational, Bayesian random effects models, 177 signalized intersections with 12318 crashes, 2000-2005	Regression analysis between intersection characteristics and crash occurrence	-	-

2.3 CONCLUSION

Regarding the effects of the number of conflict points on road safety, it appears that an increase of the number of conflict points tends to increase crash frequency, however effects of the number of conflict points were analysed mostly through effects of the (total) number of (right-turn, left-turn or through) lanes.
The majority studies on accident frequency indicate that an increase in the number of lanes, and therefore an increase in the number of conflict points tend to increase crash frequency or that intersections with less lanes (and therefore less conflict points) tend to have lower number of crashes. Whereas some studies show this for the total number of lanes in general, mostly with statistically significant effects, some studies show this tendency for specific types of lanes (e.g. right-turn, left-turn and through lane) as well as for specific crash types: for example an increase in the number of left-turn lanes on major and minor road increases crash frequency in general or for angle-crashes in particular.

However – especially for specific crash types – some studies on accident frequency also show different effects: e.g. a (significant) decrease in rear-end or crossing-crashes with an increase of the number of through lanes on the entering approach. Thus it might be that for some specific crash types an additional lane which is connected with an addition of conflict points could in some cases reduce crash risk.

Summarizing, a higher number of conflict points tends to increase crash risk in general, however it might be that for specific crash types an additional lane and with it an addition of conflict points could nevertheless probably reduce crash risk.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

Literature search was conducted in March and April 2016. It was carried out in four databases with similar search strategies. Following databases were browsed through during the literature search: 'Scopus', 'Science Direct', 'TRID' and 'Taylor and Francis Online'. Detailed search terms, as well as their linkage with logical operators and combined queries are shown in the following tables. The study scope did not exclude countries or source types like "Journal" or "Project". In some of the searches remaining studies were limited to subject areas (e.g. "Engineering"). Out of the overall 351 potentially eligible studies, after screening the abstracts of these 351 studies only from 50 the full-text were obtained and only 5 were coded and included in the synopsis. Other already known or during the literature search occasionally (e.g. via Google) found studies as well as studies found in the literature search for other topics and including effects for number of conflict points were added as additional studies (8). The reference lists of the studies were only partly checked.

Table 3 Literature search strategy, database: Scopus

search no.	search terms / operators / combined queries	hits
#1	(TITLE-ABS-KEY ("conflict points" OR "Risk" OR "crash") AND TITLE-ABS-KEY ("intersection" OR "junctioN")) AND PUBYEAR > 1989	**10,414**
#2	(TITLE-ABS-KEY ("conflict points" OR "crash" OR "safety") AND TITLE-ABS-KEY ("intersection" OR "junctioN")) AND PUBYEAR > 1989	**6,984**
#3	(TITLE-ABS-KEY ("conflict" AND "points" AND "safety" OR "crash" OR "risk" OR "regression") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	**98**

Table 4 Literature search strategy, database: ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	pub-date > 1989 and "conflict points" AND "risk"	**352**
#2	pub-date > 1989 and "conflict points" AND "risk" AND "junction" OR "intersection"	**148**

Table 5 Literature search strategy, database: TRID

search no.	search terms / operators / combined queries	hits
#1	"conflict points" AND "intersection" OR "junction"	**2764**
#2	"conflict points"	**131**
#3	"conflict points" AND "risk"	**19**

Table 6 Literature search strategy, database: Taylor & Francis Online

search no.	search terms / operators / combined queries	hits
#1	"conflict point" AND "intersection" AND "crash"	**86**

Table 7 Results Literature Search

Database	**Hits**
Scopus (remaining papers after several limitations/exclusions)	98
Science Direct	148
TRID	19
Taylor & Francis Online	86
Total number of studies to screen title/ abstract	**351**

The final 13 studies included in the synopsis indicate that the topic has been investigated to a great extent. The prioritizing criteria for coding were the following, however all studies codable and suitable for the topic were coded.

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

No meta-analyses were found.

3.1.2 Exploratory analysis of results

Table 8 presents an overview of the main outcomes of the coded studies.

Table 8 Main outcomes of coded studies on number of conflict points

Author, Year, Country	**Exposure variable**	**Outcome variable / Outcome type**	**Effects**		**Main outcome - description**
Abdel-Aty, 2006, United States	Number of lanes	Crash count / All	↗	r=0,1298, p<0,0001	Significant negative association between number of lanes and crash occurrence
	Exclusive right-turn lanes - major roadway	Crash count / All	↘	r=-0,202 , p<0,0001	Significant positive association between exclusive right-turn lanes on major approach and crash reduction
	Exclusive right-turn lanes - minor roadway	Crash count / All	↘	r=-0,2966, p<0,0001	Significant positive association between exclusive right-turn lanes on minor approach and crash reduction
Abdel-Aty, 2011, United States	Number of lanes	Crash count / 4x2, 4x4, 4x6 and 4x8 intersections	-	r=0,0443, p=0,9408	Non-significant association between number of lanes and angle-crash occurrence
	Number of lanes	Crash count / 3x2, 3x3, 3x4, 3x5, 3x6, 3x8 intersections	↗	r=0,9531, p=0,0069	Significant negative association between number of lanes and angle-crash occurrence

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Number of lanes	Crash count / 2x7, 2x8 intersections	-	r=0,8813, p=0,2660	Non-significant association between number of lanes and angle-crash occurrence
	Number of lanes	Crash count / 2x4, 2x5, 2x6 intersections	-	r=0,2661, p=0,3430	Non-significant association between number of lanes and angle-crash occurrence
Dong, 2014a, United States	Number of left-turn lanes on major approach	Crash count / Car crashes	-	r=0,054, 95% CI	No significant effect of number of left-turn lanes on car crashes
	Number of left-turn lanes on minor approach	Crash count / Car crashes	-	r=0,009, 95% CI	No significant effect of number of left-turn lanes on car crashes
	Number of exclusive right-turn lanes on major approach	Crash count / Car crashes	↗	r=0,023, 95% CI	Significant negative effect of number of exclusive right-turn lanes on car crashes
	Number of exclusive right-turn lanes on minor approach	Crash count / Car crashes	↗	r=0,014, 95% CI	Significant negative effect of number of exclusive right-turn lanes on car crashes
	Number of left-turn lanes on major approach	Crash count / Car-truck crashes	↗	r=0,077, 95% CI	Significant negative effect of number of left-turn lanes on car-truck crashes
	Number of left-turn lanes on minor approach	Crash count / Car-truck crashes	↗	r=0,022, 95% CI	Significant negative effect of number of left-turn lanes on car-truck crashes
	Number of exclusive right-turn lanes on major approach	Crash count / Car-truck crashes	-	r=0,045, 95% CI	No significant effect of number of exclusive right-turn lanes on car-truck crashes
	Number of exclusive right-turn lanes on minor approach	Crash count / Car-truck crashes	-	r=0,067, 95% CI	No significant effect of number of exclusive right-turn lanes on car-truck crashes

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Number of left-turn lanes on major approach	Crash count / Truck crashes	↗	r=0,089, 95% CI	Significant negative effect of number of left-turn lanes on truck crashes
	Number of left-turn lanes on minor approach	Crash count / Truck crashes	↗	r=0,062, 95% CI	Significant negative effect of number of left-turn lanes on truck crashes
	Number of exclusive right-turn lanes on major approach	Crash count / Truck crashes	-	r=0,069, 95% CI	Non-significant effect of number of exclusive right-turn lanes on truck crashes
	Number of exclusive right-turn lanes on minor approach	Crash count / Truck crashes	-	r=0,041, 95% CI	Non-significant effect of number of exclusive right-turn lanes on truck crashes
Dong, 2014b, United States	Number of left-turn lanes on major approach	Crash count / Car crashes	↗	r=0,665, 95% CI	Significant negative effect of number of left-turn lanes on car crashes
	Number of left-turn lanes on minor approach	Crash count / Car crashes	↗	r=1,419, 95% CI	Significant negative effect of number of left-turn lanes on car crashes
	Number of exclusive right-turn lanes on major approach	Crash count / Car crashes	↗	r=1,456, 95% CI	Significant negative effect of number of exclusive right-turn lanes on car crashes
	Number of exclusive right-turn lanes on minor approach	Crash count / Car crashes	↗	r=3,646, 95% CI	Significant negative effect of number of exclusive right-turn lanes on car crashes
	Number of left-turn lanes on major approach	Crash count / Car-truck crashes	↗	r=1,27, 95% CI	Significant negative effect of number of left-turn lanes on car-truck crashes

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Number of left-turn lanes on minor approach	Crash count / Car-truck crashes	↗	r=2,275, 95% CI	Significant negative effect of number of left-turn lanes on car-truck crashes
	Number of exclusive right-turn lanes on major approach	Crash count / Car-truck crashes	↗	r=1,154, 95% CI	Significant negative effect of number of exclusive right-turn lanes on car-truck crashes
	Number of exclusive right-turn lanes on minor approach	Crash count / Car-truck crashes	↗	r=2,723, 95% CI	Significant negative effect of number of exclusive right-turn lanes on car-truck crashes
	Number of left-turn lanes on major approach	Crash count / Truck crashes	↗	r=1,746, 95% CI	Significant negative effect of number of left-turn lanes on truck crashes
	Number of left-turn lanes on minor approach	Crash count / Truck crashes	↗	r=3,182, 95% CI	Significant negative effect of number of left-turn lanes on truck crashes
	Number of exclusive right-turn lanes on major approach	Crash count / Truck crashes	↗	r=0,866, 95% CI	Significant negative effect of number of exclusive right-turn lanes on truck crashes
	Number of exclusive right-turn lanes on minor approach	Crash count / Truck crashes	↗	r=2,186, 95% CI	Significant negative effect of number of exclusive right-turn lanes on truck crashes
Haleem, 2010, United States	Number of lanes	Injury severity (severe) 1x2, 1x3, 1x4 intersections	↗	r=4,8632, p<0,0001	Significant increase of crash severity at less complex intersections
	Number of lanes	Injury severity (severe) / 2x2, 2x3 intersections	-	r=-0,1546, p=0,4701	Non-significant decrease of crash severity at complex intersections
	Number of lanes	Injury severity (severe) / 2x4, 2x5, 2x6 intersections	-	r=0,0419, p=0,8391	Non-significant increase of crash severity at complex intersections

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Number of lanes	Injury severity (severe) / 2x7, 2x8 intersections	-	r=0,1258, p=0,6132	Non-significant increase of crash severity at complex intersections
	Number of lanes	Injury severity (severe) / 3x2, 3x3, 3x4, 3x5, 3x6, 3x8 intersections	-	r=0,0174, p=0,9367	Non-significant increase of crash severity at complex intersections
Haque, 2010, Singapore	Additional lane on major approach	Crash count / Crossroad	↗	+13,3%	Significant negative effect of number of lanes on major approach on roads safety (percent accident rise) at crossroads
	Additional lane on minor approach	Crash count / Crossroad	↗	+18,6%	Significant negative effect of number of lanes on minor approach on road safety (percent accident rise) at crossroads
	Additional lane on minor approach	Crash count / T-intersection	↗	+72,9%	Significant negative effect of number of lanes on minor approach on road safety (percent accident rise) at T-intersections
Qin, 2010, United States	Number of lanes on major roadway	Crash count / 2-lane roadway	↘	r=-0,1909, p=0,0016	Significant positive effect of 2-lane intersections on road safety compared to 4-lane intersections
Wadhwa, 2006, Australia	Number of crossing conflict points (0)	Fatality rate / Roundabout	-	0,191%	Percent of fatal crashes
	Number of crossing conflict points (1)	Fatality rate / T-arm signalized (1)	-	0,438%	Percent of fatal crashes
	Number of crossing conflict points (2)	Fatality rate / Crossroad signalized	-	0,532%	Percent of fatal crashes
	Number of crossing conflict points (3)	Fatality rate / T-arm unsignalized	-	0,967%	Percent of fatal crashes
	Number of crossing conflict points (16)	Fatality rate / Crossroad unsignalized	-	1,05%	Percent of fatal crashes

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
Wang, 1999, Japan	Lane number of entering approach	Crash count	↘	r=-0,037, 85% CI	Significant positive effect of number of lanes on entering approach on rear-end crashes
Wang, 2001, Japan	Existence of more right-turn lanes (more than 2)	Crash count	↗	r=0,513, 85% CI	Significant negative effect of more right-turn lanes on crashes with crossing vehicles
	Number of through lanes on entering approach	Crash count	↘	r=-0,0225, 85% CI	Significant positive effect of number of through lanes on entering approach on crashes with crossing vehicles
Wang, 2004, Japan	Number of right-turn lanes on opposing approach	Crash count / Bicycle and motor vehicle crashes	↗	r=0,581, p=0,03	Significant negative effect of number of right-turn lanes on BMV-crashes (bicycles and left-turning vehicles)
	Number of outgoing lanes on left approach	Crash count / Bicycle and motor vehicle crashes	↗	r=0,424, p=0,000	Significant negative effect of number of outgoing lanes on left approach on BMV-crashes with regard to (bicycles and left-turning vehicles)
	Number of intersection approaches sheltered by elevated roadways	Crash count / Bicycle and motor vehicle crashes	↗	r=0,462, p=0,04	Significant negative effect of intersection approaches sheltered by elevated roadways on on BMV-crashes (bicycles and right-turning motor vehicles)
	Number of right-turn lanes on entering approach	Crash count / Bicycle and motor vehicle crashes	↗	r=0,545, p=0,02	Significant negative effect of number of right-turn lanes on entering approach on BMV-crashes (bicycles and right-turning motor vehicles)
Wang, 2008, United States	Number of through lanes on opposing approach	Crash count / >= 3 lanes, left-turning traffic collides with on-coming through traffic	↗	r=0,4604, p=0,0306	Significant negative effect of number of through lanes on opposing approach for left-turning traffic collisions with on-coming through traffic
	Number of through lanes on opposing approach	Crash count /2 lanes, left-turning traffic collides with on-coming through traffic	↗	r=0,4168, p=0,0145	Significant negative effect of number of through lanes on opposing approach for left-turning traffic collisions with on-coming through traffic

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Number of through lanes on opposing approach	Crash count / >= 4 lanes, left-turning traffic collides with near-side crossing through traffic	-	r=-2,0504, p=0,0671	No significant effect of number of through lanes on opposing approach for left-turning traffic collisions with near-side crossing through traffic
	Number of through lanes on opposing approach	Crash count / 3 lanes, left-turning traffic collides with near-side crossing through traffic	↘	r=-1,1955, p=0,0005	Significant positive effect of number of through lanes on opposing approach for left-turning traffic collisions with near-side crossing through traffic
	Number of through lanes on opposing approach	Crash count / 2 lanes, left-turning traffic collides with near-side crossing through traffic	↘	r=-0,5207, p=0,0197	Significant positive effect of number of through lanes on opposing approach for left-turning traffic collisions with near-side crossing through traffic
	Number of left-turn lanes on entering approach	Crash count / >=2 lanes, left-turning vehicle collides with other left-turning vehicles from the same approach	-	r= 0,07, p=0,8613	No significant effect of number of left-turn lanes on entering approach for left-turning vehicle collisions with other left-turning vehicles from the same approach
	Number of left-turn lanes on entering approach	Crash count / 1 lane, left-turning vehicle collides with other left-turning vehicles from the same approach	↘	r=-1,2508, p=0,0004	Significant positive effect of number of left-turn lanes on entering approach for left-turning vehicle collisions with other left-turning vehicles from the same approach
	Number of through lanes on opposing approach	Crash count / >=3 lanes, left-turning vehicles merge into receiving lane of the far side approach	↘	r=-2,0717, p=0,0003	Significant positive effect of number of through lanes on opposing approach for left-turning vehicles merging into receiving lane of the far side approach collisions
	Number of through lanes on opposing approach	Crash count / 2 lanes, left-turning vehicles merge into receiving lane of the far side approach	↘	r=-0,5349, p=0,0116	Significant positive effect of number of through lanes on opposing approach for left-turning vehicles merging into receiving lane of the far side approach collisions

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
Wang, 2014, United States	Number of left-turn lanes on entering approach	Crash count / All crashes	-	r=0,1042	Non-significant negative effect of number of left-turn lanes on entering approach on road safety
	Number of right-turn lanes on entering approach	Crash count / All crashes	-	r=0,1855	Non-significant negative effect of number of right-turn lanes on entering approach on road safety
	Number of right-turn lanes on entering approach	Crash count / Rear-End	-	r=0,2514	Non-significant negative effect of number of right-turn lanes on entering approach on rear-end crashes
	Number of through lanes on entering approach	Crash count / with oncoming vehicle on opposing approach going left	-	r=0,2053	Non-significant negative effect of number of through lanes on entering approach on crashes with oncoming vehicle on opposing approach going left
	Number of through lanes on opposing approach	Crash count / with approaching vehicle going left, hitting left-coming vehicle	-	r=-0,6285	Non-significant positive effect of number of through lanes on opposing approach on crashes with approaching vehicle going left, hitting left-coming vehicle
	Number of through lanes on entering approach	Crash count / Right-Angle	-	r=-0,0970	Non-significant positive effect of number of through lanes on entering approach on right-angle crashes
	Number of through lanes on entering approach	Crash count / Sideswipe	-	r=0,1972	Non-significant negative effect of number of through lanes on entering approach on sideswipe crashes
	Number of left-turn lanes on entering approach	Crash count / Sideswipe	-	r=0,3827	Non-significant negative effect of number of left-turn lanes on entering approach on sideswipe crashes
	Number of right-turn lanes on entering approach	Crash count / Sideswipe	-	r=0,2684	Non-significant negative effect of number of right-turn lanes on entering approach on sideswipe crashes

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

3.2 FULL LIST OF STUDIES

3.2.1 List of studies

A detailed list of studies coded is presented below:

Abdel-Aty, M. & Wang, X. (2006). Crash Estimation at Signalized Intersections Along Corridors. Transportation Research Record: Journal of the Transportation Research Board, 1953, pp. 98-111.

Abdel-Aty, M. & Haleem, K. (2011). Analyzing angle crashes at unsignalized intersections using machine learning techniques. Accident Analysis and Prevention, 43, pp. 461-470.

Dong, C., Clarke, D.B., Richards, S.H., & Huang B. (2014a). Differences in passenger car and large truck involved crash frequencies at urban signalized intersections: An exploratory analysis. Accident Analysis and Prevention, 62, pp. 87-94.

Dong, C., Clarke, D.B., Yan, X., Khattak, A., & Huang, B. (2014b). Multivariate random-parameters zero-inflated negative binomialregression model: An application to estimate crash frequenciesat intersections. Accident Analysis and Prevention, 70, pp. 320-329.

Haleem, K., & Abdel-Aty, M. (2010). Examining traffic crash injury severity at unsignalized intersections. Journal of Safety Research, 41, pp. 347-357.

Haque, M.M., Chin, C.C., & Huang, H. (2010). Applying Bayesian hierarchical models to examine motorcycle crashes at signalized intersections. Accident Analysis & Prevention, 42, pp.203-212.

Qin, X., Ng, M., & Reyes, P.E. (2010). Identifying crash-prone locations with quantile regression. Accident Analysis and Prevention, 42, pp. 1531–1537.

Wadhwa, L.C., & Thomson, M. (2006). Relative safety of alternative intersection designs. Urban Transport XII: urban transport and the environment in the 21st century, pp. 379-388.

Wang, Y., Ieda, H., Saito, K., & Takahashi, K. (1999). Using Accident Observations to evaluate rear end accident risk at four-legged signalized intersections. Safety Analysis and Policy, Paper n°268.

Wang, Y., & Nihan, N.L. (2001). Quantitative Analysis on Angle-Accident Risk at Signalized Intersections. Safety Analysis and Policy.

Wang, L., & Nihan, N.L. (2004). Estimating the risk of collisions between bicycles and motor vehicles at signalized intersections.Accident Analysis and Prevention, 36, pp. 313–321.

Wang, X., & Abdel-Aty, M. (2008). Modeling left-turn crash occurrence at signalized intersections by conflicting patterns. Accident Analysis and Prevention, 40, pp. 76-88

Wang, X.; Xie, K.; & Chen, X. (2014). Systematic Approach to Hazardous-Intersection Identification and Countermeasure Development, Journal of Transportation Engineering Volume 140, Issue 6.

3.2.2 References on further background information

Dijkstra ,A. / Van Petegem, J.H. (2015): Towards safer intersections. Recommendations for intersections on 50, 80 and 100 km/h roads. 5th International Symposium on Geometric Highway Design. Vancouver.

Eccles, K.A. / Levinson, H.S. (2007): Design, Operation, and Safety of At-Grade Crossings of Exclusive Busways. TCRP Report 117. Transportation Research Board. Washington, D.C.

Elvik, R. / Høye, A. / Vaa, T. / Sørensen, M. (2009): The Handbook of Road Safety Measures. Second edition. Emerald Group. Bingley.

Synopsis 31: risk of different junction types

1 Summary

Soteropoulos, A. & Stadlbauer, S., September 2016

1.1 COLOUR CODE: YELLOW

From the effects of the type of junction (constructional, not signalisation) on road safety presented in international literature it seems that junctions with more approaches/arms like crossroads (4 arms) or multiple (>4 arms) have higher crash risks and lead to a higher crash severity compared to 3-legged junctions (T-junctions).

1.2 KEYWORDS

Type of junction; intersection; approaches; configuration; legs; arms; three-legged junction; four-legged junction; multiple-legged junction

1.3 ABSTRACT

Regarding the effect of the type of junction on road safety, studies on accident frequency mostly show a higher crash risk for junctions with four or more arms compared to 3-legged junctions. Those effects were often statistically significant. Furthermore studies on accident severity mostly indicated that junctions with four or more legs increase crash severity compared to 3-legged junctions. Summarizing, it seems that junctions with more approaches/arms like crossroads (4 arms) or multiple (>4 arms) have higher crash risks and lead to a higher crash severity compared to 3-legged junctions (T-junctions). Also compared to roundabouts intersections tend to have a higher crash risk in general. When it comes to crashes roundabouts can significantly reduce the severity of crashes.

1.4 BACKGROUND

1.4.1 What is type of junction?

Type of junction refers to the different types of junctions/intersections existing in road design, mainly dependent on the environment, the road type and the capacity (Yannis et al. 2011). Junction types differ mainly in the number of legs/approaches/arms at the junction e.g. crossroads (4-arm), T-junctions (3-arm), staggered junctions (two T-junctions) or Multiple (> 4 arms); crossroads and T-junctions are the most common. In addition, also for intersections with the same number of approaches several types exist: e.g. Y-intersection, a T-intersection with 3 arms of equal size (Wadwha and Thomson 2006). Furthermore, junctions can be signalized (with traffic signals) or unsignalized. Moreover roundabouts and railway level crossings are also junction types (Elvik et al. 2009). However these are special types of intersections and were for the most part not part of the primer examination (Wadwha and Thomson 2006).

1.4.2 How does type of junction affect road safety?

Junctions with four approaches (crossroads) place higher demands on road users alertness than junctions with three approaches – T-junctions (Elvik et al.2009). Moreover multiple-legged intersections usually have more conflicting traffic flows with an insufficient sight distance (Chiou et al. 2013). In addition, crossroads – because they have more approaching lanes – have a higher likelihood of side impact crashes (Tay and Rifaat 2007). Furthermore motor-vehicle flows and speeds are usually greater in 4- or multiple-legged intersections compared to 3-legged intersections (Ukkusuri et al. 2012). At 3-legged intersections speed (of the first or second vehicle) is often reduced because at 3-legged intersections one vehicle always has to make a turn – at least on the third leg, the one without on-coming traffic (Chiou et al. 2013). Moreover 3-legged intersections have fewer conflicting points (Qin et al. 2010). However shorter sight distance is a problem often associated with T/Y-type intersections as well (Helai et al. 2008).

1.4.3 Which safety outcomes are affected by type of junction?

In the international literature, the effect of type of junction on road safety has been measured on two basic outcomes, namely accident frequency (number of crashes occurred) and accident severity (severity of injuries of occupants given that an accident has occurred).

1.4.4 How is the effect of type of junction studied?

International literature indicated that the effect of type of junction on road safety is usually examined by applying multivariable linear statistical models. In accident frequency models, the relationship between type of junction and number of crashes is investigated mostly with negative binomial or Poisson models. In accident severity models, the studies identified mostly applied logistic regression or ordered probit models. Moreover some studies only undertook a crash data analysis and calculated crash rates for different junction types. The studies identified focused on junctions at urban roads as well as on junctions at rural roads. Most research has been done in the United States but also two European studies (Belgium and the Netherlands) were found.

1.5 OVERVIEW RESULTS

Regarding the effects of type of junction on road safety, studies mostly show a higher crash risk for junctions with four or more arms compared to 3-legged junctions and that junctions with four or more legs increase crash severity compared to 3-legged junctions. Thus it seems that in general junctions with more approaches/arms like crossroads (4 arms) or multiple (>4 arms) have higher crash risks and lead to a higher crash severity compared to 3-legged junctions (T-junctions). Furthermore roundabouts can significantly reduce the accident risk and at the same time they seem to decrease the accident severity when it comes to crashes.
These results were primarily found for motor vehicle crashes and since most research was carried out in North America, Asia and Australia the transferability may be questioned because of potential regional characteristics.

1.6 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound. However some of the studies used only small samples for investigation.

Overall, the topic has been deeply studied (number of relevant studies is 19). Research mainly focused on crashes with motor vehicles, but some studies focused on pedestrians and bicycles. Moreover research was mostly carried out in the United States, Australia and Singapore and is probably influenced by national specifications. Two European studies were identified.

2 Scientific overview

2.1 RESULTS

From the studies identified in the international literature it seems that junctions with more approaches/arms like crossroads (4 arms) or multiple (>4 arms) have higher crash risks and lead to a higher crash severity compared to 3-legged junctions (T-junctions) or roundabouts (see Figure 1).

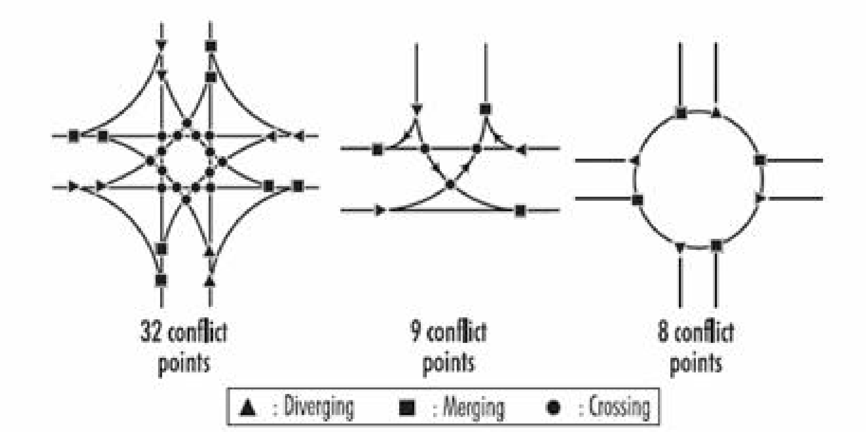


Figure 1. Number of conflict points per junction type

Studies on accident frequency mostly show a higher crash risk for junctions with four or more arms compared with 3-legged intersections. Abdel-Aty and Wang (2006) for example indicate, that 3-legged intersections significantly reduce crash risk compared with 4-legged intersections. Also Qin et al. (2010) indicate that 3-legged intersections have a significant lower crash frequency than 4-legged intersections. Further results of Poch and Mannering (1996) indicate a significant negative effect of the number of intersection legs on the occurrence of angle-crashes (higher risk of angle-crashes). Moreover results of Dumbaugh and Rae (2009) – focussing on the intersection count on neighbourhood level – show that 4-leg intersections were associated with a small significant increase in total crashes, while 3-leg intersections also had a slightly positive effect on total crashes, however statistically insignificant. Xie et al. (2013) indicate that 3-legged intersections had a lower crash rate than 4-legged intersections (25% lower), however this positive effect of T-intersections on crash occurrence compared to crossroads was statistically not significant.

Not only for motor-vehicles but also for pedestrians and bicyclists similar effects were found. Pulugurtha and Sambhara (2011) for example indicate that the number of pedestrian crashes (significantly) increases with the number of approaches at an intersection and illustrate that this is likely because the risk for pedestrians is relatively high at 4-legged signalized intersections compared to 3-legged signalized intersections. Ukkusuri et al. (2012) – focussing on the intersection count on neighbourhood level – indicate that the presence of 4- or 5-way intersections significantly increased the frequency of pedestrian-motor vehicle-crashes, while 3-way intersections are associated with reduced likelihood of crashes. Also risk factors identified in the iRAP Factsheet indicate that crash risk for motor-vehicles, pedestrians and bicyclists is higher at 4-legged intersections (different types) compared with 3-legged intersections (different type).

However in some studies (for specific crash types) contrary estimates were presented. Polders et al. (2014) for example indicate that rear-end crashes appear to be more likely at (signalized) intersections with three arms compared to (signalized) intersections with four arms. Furthermore results of Xu et al. (2014) indicate that the existence of four or more approaches (crossroad or multiple) significantly decreases the likelihood of slight injury crashes, although no effects were presented for severe injury crashes and moreover the authors describe that this is specific for the local/national environment due to lower design standards. In addition for bicycle-motor vehicle-crashes (when cyclists has right of way) Schepers et al. (2011) indicate that compared to T-intersections, crossroads decrease accident risk, however not statistically significant.

The two studies on accident frequency which only undertook a crash data analysis of fatal crashes (Langford and Koppel 2006; Wadhwa and Thomson 2006) tend to show higher fatality rates for cross-intersections compared to T-intersections (Wadhwa and Thomson 2006), however Langford and Koppel (2006) – regarding older driver fatal crashes – also illustrate that those crashes were evenly spread across cross-intersections and T-junctions, and this was the case for the other age groups as well.
It should be emphasized however that these two studies only undertook a crash data analysis and effects were not significant in a statistical way.

Studies on accident severity mostly indicated that intersections with four or more legs increase crash severity compared to 3-legged intersections. Anowar et al. (2014) for example illustrate that compared to cross intersections, crash severity tended to be significantly lower at staggered or T-junctions (and roundabouts). Furthermore results of Barua et al. (2010) indicate that compared to T-intersections on straight sections of highway, cross-intersections on straight sections of highway as well as cross-intersections on curves are associated with a significant higher fatality risk of intersection crashes. Tay and Rifaat (2007) also indicate that compared to T-intersections, cross-intersections significantly increase crash severity, this was also the case for Y-intersections, however not statistically significant. Moreover Dumbaugh and Rae (2009) – focussing on the intersection count on neighbourhood level – illustrate that 4-legged intersections were associated with significant increases in injurious crashes, whereas 3-leg intersections were associated with fewer injurious crashes, although not statistically significant. Furthermore both 3- and 4-leg intersections were associated with significantly lower incidences of fatal crashes likely due to the fact that intersections force one or more streams to decelerate or come to a stop, which reduces vehicle speeds an thus crash severity. In addition results of Chiou et al. (2013) indicate that multiple-legged intersections don't affect injury severity of the first party (driver or rider who has to take greater responsibility), but significantly increase injury severity of the second party (not at fault), however this was also the case for 3-legged intersections. Also effects identified in the iRAP Factsheet indicate that 4-legged intersections (different types) increase accident severity compared to 3-legged intersections for motor-vehicles as well as for bicyclists.

However, in some studies on accident severity contrary estimates were presented. Helai et al. (2008) for example indicate that compared to other types of intersections, T- or Y-intersections are associated with a significant higher accident severity (higher odds of high severity), whereas crossroads (X-type intersections) have an averagely positive effect on reducing the crash severity, however not statistically significant. Boufous et al. (2008) – deploying a multiple linear regression analysis regarding injury severity of older people – illustrate in fact that complex intersections such as Y-Junctions, T-junctions, roundabouts and multiple intersections were more likely to result in severe injuries, however compared to non-intersections. For cross intersections no effects were presented.

Table 1 gives an overview of the results of the vote-count analysis. Results show that junctions with more approaches/arms like crossroads or multiple (>4 arms) in general tend to have higher crash severity. For accident frequency it seems that three-legged junctions have a lower crash risk.

Table 1 Results of the vote-count analysis

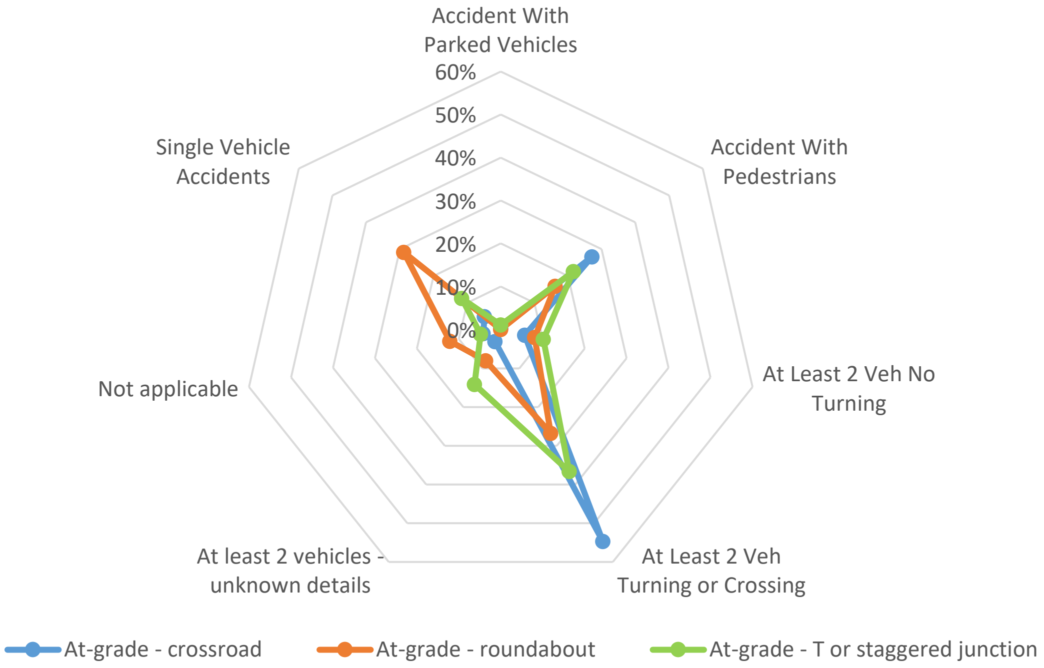
	Total number of effects tested	**Result (number of effects)***				**Result (% of effects)**	
		↗	-	↘		↗	↘
Accident Frequency**	**20**	**4**	**10**	**6**		**40%**	**60%**
three-legged	8	1	4	3		25%	75%
staggered	-	-	-	-		-	-
crossroads	8	1	6	1		50%	50%
multiple	2	1	0	1		50%	50%
roundabouts	-	-	-	-		-	-
other	-	-	-	-		-	-
number of legs	2	1	0	1		50%	50%
Accident Severity**	**35**	**9**	**19**	**7**		**56%**	**44%**
three-legged	11	2	6	3		40%	60%
staggered	2	1	0	1		50%	50%
crossroads	12	4	8	0		100%	0%
multiple	3	2	1	0		100%	0%
roundabouts	4	0	2	2		0%	100%
other	3	0	2	1		0%	100%

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)
**Since exposures differ, the summarized effects for accident frequency and accident severity can't be interpreted as main results.

Crash characteristics

Analysis of the CARE database showed that the type of junction has influences regarding the accident type. Figure 2 – a comparison of different junction types in regard to the accident type – reveals that for both crossroads and T- or staggered junction crashes are most often turning or crossing crashes, but this is especially the case for crossroads. Compared to crossroads, crashes at T- or staggered junctions are more often single vehicle crashes. This is also the case for roundabouts.

Figure 2: Differences of junction types (crossroads, T- or staggered junctions and roundabouts) in regard to the accident type



This crash scenario analysis was conducted using cases from the CARE Database, considering all fatal crashes[1] recorded in year 2013. In total, records from 23 577 crashes which occurred in 28 European countries were analysed. CARE Database comprises detailed data on individual crashes as collected by the Member States. Data are recorded according to a Common Accident Data Set (CADaS) consisting of a minimum set of standardised data elements, which allows for comparable road accident data to be available in Europe. Accident reports note all factors which were present at a crash. This does not mean that the noted factor was a contributory factor towards the crash. For the current analysis all crashes at crossroads were compared to all crashes at roundabouts and T-or staggered junctions (type of junction). Note that, the risk factor is identified in relation to the involved party who was considered most at fault.

[1] Data refer to those crashes where at least a person was fatally injured (death within 30 days of the road accident, confirmed suicide and natural death are not included).

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

Overall 18 high quality studies as well as one iRAP factsheet on type of junction were selected and coded. 10 studies focused on accident frequency and 6 studies focused on accident severity. 2 studies only undertook a crash data analysis. In order to examine the relationship between type of junction and outcome indicators, studies on accident frequency and on accident severity deployed multivariable statistical models (i.e. negative binomial, logistic regression etc.) as a method of examining the topic and controlled for other geometrical characteristics and traffic flow as well.

Studies on accident frequency mainly deployed negative binomial or Poisson models. Studies on accident severity mostly deployed logistic regression or ordered probit models. In addition some studies (Langford and Koppel 2006; Wadhwa and Thomson 2006) only undertook a crash data analysis and calculated crash rates for different junction types.

The studies identified focused on junctions at urban roads as well as on junctions on rural roads. Most studies focused on motor-vehicle crashes, however in some studies (e.g. Pulugurtha and Sambhara 2011; Polders et al. 2014) also other road user types (pedestrians, bicyclists) were focus of the research. Most research has been done in the United States (6 studies), Australia (3 studies), Singapore (3 studies) and China (2 studies). Also two European studies (Belgium and the Netherlands) were found.

Table 2 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 2 Description of coded studies

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Abdel-Aty, 2006, United States	Observational, negative binomial regression including 476 signalized intersections between 1999 and 2000	Regression analysis between intersection characteristics and crash occurrence	Intersections with different characteristics	-
Anowar, 2014, Bangladesh	Observational, partially constrained generalized ordered logit model (PCGOLM) including data of 4471 records, 1998-2006	Regression analysis between intersection characteristics and crash occurrence	Crossroads	Focus on accident severity at T-intersections
Barua, 2010, Canada	Observational, logistic regression model, data of 3544 crashes, 2003-2005	Regression analysis between intersection characteristics and crash frequency	T-intersections on straight section	Road network was limited to rural roads, focus on fatal crashes
Boufous, 2008, Australia	Observational, multivariate regression model, data of 825 hospitalized persons, 2000-2001	Regression between intersection characteristics and crash occurrence	Non-intersections	Focus on severe injuries of older drivers
Chiou, 2013, Taiwan	Observational, novel bivariate generalised ordered probit model (BGOP), data of 2661 two-vehicle crashes at signalised intersections, 2006-2007	Regression between intersection characteristics and crash occurrence	-	Results for first party (driver or rider who who has to take greater responsibility) and second party, focus on accident severity

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Dumbaugh, 2009, United States	Observational, Cross-sectional, negative binomial regression model, data of 150626 crashes, 2004-2006	Regression between road network characteristics and crash occurrence	-	Road network was limited to urban roads, focus on accident severity
Helai, 2008, Singapore	Observational, bayesian hierarchical analysis, 4095 crashes at signalized intersections, 2003-2005	Regression analysis between intersection characteristics and crash occurrence	-	Road network was limited to rural roads, focus on accident severity
iRAP, 2013, -	Factsheet, risk factors with regard to motorised vehicles, no details among method or data	Risk ratio for Cars and PTW	T-intersections	likelihood and severity risk values at crossroads
Langford, 2006, Australia	Crash data analysis of 6338 fatal crashes, 1996-1999	-	middle-aged drivers (40-55 years)	Focus on fatal crashes
Poch, 1996, United States	Observational, negative binomial model, observational design including intersections (n=63) with 1396 crashes between 1987 and 1993	Regression analysis between intersection characteristics and crash occurrence	-	Road network was limited to urban roads
Polders, 2014, Belgium	Observational, logistic regression analysis, 1295 police-reported crashes at 87 signalized, intersections, 2007-2011	Regression analysis between intersection characteristics and crash occurrence	Crossroads	Focus on crash types (rear-end) at T-intersections
Pulugurtha, 2011, United States	Observational, generalized linear pedestrian crash estimation model based on a negative binomial model, 176 randomly selected signalized intersections, 2003-2007	Regression analysis between road characteristics and crash occurrence	-	Road network was limited to rural roads
Qin, 2010, United States	Observational, quantile regression model, 1710 intersections between 2001 and 2003	Regression analysis between intersection characteristics and crash occurrence	4-lane intersections	-
Schepers, 2011, Netherlands	Observational, negative binomial regression model, 540 priority intersections, 490 were susceptible to type I crashes (type I crashes, by definition, cannot happen at single separate bicycle crossings) and 524 to type II crashes, 2005-2008	Regression analysis between intersection characteristics and crash occurrence	T-intersection or single separate bicycle crossing	-
Tay, 2007, Singapore	Observational, ordered probit model, data of 23065 crashes at intersections, 1992-2002	Regression analysis between intersection characteristics and crash occurrence	T-intersections	Road network was limited to urban roads, Focus on accident severity
Ukkusuri, 2012, Unites States	Observational, negative binomial model, crash data from 2002-2006 (no number presented)	Regression analysis between road network attributes and crash risk	-	Road network was limited to rural roads, focus on accident severity
Wadhwa, 2006,	Crash data analysis of 2748 intersections, 1999-2002	-	-	Only fatal crashes

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Australia				
Xie, 2013, China	Observational, hierarchical negative binomial mode, data of 195 signalized intersections, 2009	Regression analysis between intersection characteristics and crash occurrence	Crossroads	Road network was limited to urban roads, compares T-intersections with crossroads
Xu, 2014, China	Observational, two-stage bivariae logistic-Tobit model, 420 observations form 262 signalized intersections, 2002-2003	Regression analysis between intersection characteristics and crash occurrence	-	Road network was limited to urban roads, crash risk for intersections with 4 or more approaches

2.3 CONCLUSION

Studies on the effect of type of junction on road safety identified in the international literature focused on accident frequency and as well as on accident severity.

Studies on accident frequency mostly show a higher crash risk for junctions with four or more arms compared to 3-legged junctions. Those effects were often statistically significant. Furthermore not only for motor-vehicles but also for pedestrians and bicyclists similar effects were found. Studies on accident severity also mostly indicated that junctions with four or more legs increase crash severity compared to 3-legged junctions.

Summarizing, it seems that junctions with more approaches/arms like crossroads (4 arms) or multiple (>4 arms) have higher crash risks and lead to a higher crash severity compared to 3-legged junctions (T-junctions).

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

Literature search was conducted in March and April 2016. It was carried out in four databases with similar search strategies. Following databases were browsed through during the literature search: 'Scopus', 'Science Direct', 'TRID' and 'Taylor and Francis Online'. Detailed search terms, as well as their linkage with logical operators and combined queries are shown in the following tables. The study scope did not exclude countries or source types like "Journal" or "Project". In some of the searches remaining studies were limited to subject areas (e.g. "Engineering"). Out of the overall 594 potentially eligible studies (duplicates included), after screening the abstracts of these 594 studies, only 54 the full-text were obtained and only 5 were coded and included in the synopsis. An additional 14 studies were identified due to other already known or during the literature search occasionally (e.g. via Google) found studies as well as studies found in the literature search for other topics and including effects for type of junction. The reference lists of the studies were only partly checked.

Table 3 Literature search strategy, database: Scopus

search no.	search terms / operators / combined queries	hits
#1	(TITLE-ABS-KEY ("type" OR "crash" OR "risk") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	**53,902**
#2	(TITLE-ABS-KEY ("type" AND "crash" OR "risk") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989 AND (LIMIT-TO (SUBJAREA , "ENGI"))	**421**
#3	(TITLE-ABS-KEY ("type" AND "crash" AND "risk") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	**113**

Table 4 Literature search strategy, database: ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	pub-date > 1989 and "type" AND "risk" OR "crash" AND "intersection" OR "junction"	**109,191**
#2	pub-date > 1989 and "type" AND "risk" AND "crash" AND "intersection" OR "junction".	**4,015**
#3	pub-date > 1989 and "type" AND "risk" AND "crash" AND "intersection" AND "junction"	**432**
#4	pub-date > 1989 and "rail" AND "crossing" AND "crash" AND "risk"[All Sources(Engineering)].	**384**
#5	pub-date > 1989 and "type" AND "risk" AND "crash" AND "intersection" AND "junction"[All Sources(Engineering)].	**254**

Table 5 Literature search strategy, database: TRID

search no.	search terms / operators / combined queries	hits
#1	"type" AND "risk" OR "crash" AND "intersection" OR "junction"	**15,000**
#2	"type" AND "risk" OR "crash" AND "intersection" OR "junction" [All Sources(Freight Transportation, Passenger Transportation, Pedestrian Transportation, Public Transportation, Transportation (General))]	**6,957**

#3	"type" AND "intersection" OR "junction" OR "risk" Sources(Passenger Transportation)	**910**
#4	TITLE-ABS-KEY ("intersection" OR "junction") AND "type" AND "crash" OR "risk" Sources(Highways, Pedestrians or Bicyclists, Safety and Humans Factors, Transportation (General))	**204**

Table 6 Literature search strategy, database: Taylor & Francis Online

search no.	search terms / operators / combined queries	hits
#1	"intersection" AND "type" AND "crash"	**1,097**
#2	"intersection" AND "type" AND "crash" AND ABSTRACT ("risk" AND "regression")	**23**

Table 7 Results Literature Search

Database	Hits
Scopus (remaining papers after several limitations/exclusions)	113
Science Direct	254
TRID	204
Taylor & Francis Online	23
Total number of studies to screen title/ abstract	**594**

The final 13 studies included in the synopsis indicate that the topic has been investigated to a great extent. Studies selected to code were prioritized as follows, however all studies codable and suitable for the topic were coded.

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

No meta-analyses were found.

3.1.2 Exploratory analysis of results

Table 8 presents an overview of the main outcomes of the coded studies.

Table 8 Main outcomes of coded studies on type of junction

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
Abdel-Aty, 2006, United States	Type of junction	Crash count T-intersection	↘	r=-0,3341, p<0,0001	Significant positive association between type of junction (T-intersection) and crash severity compared to crossroads
Anowar, 2014, Bangladesh	Type of junction	Crash severity / minor-severe, T-intersections	↘	r=-0,0855	Significant positive association between type of junction (T-intersection) and crash severity compared to crossroads

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Type of junction	Crash severity / minor-severe, staggered	↘	r=-0,0805	Significant positive association between type of junction (staggered) and crash severity compared to crossroads
	Type of junction	Crash severity / damage only-minor, roundabout	↘	r=-0,5312	Significant positive association between type of junction (roundabout) and crash severity compared to crossroads
	Type of junction	Crash severity / minor-severe, roundabout	↘	r=-0,3740	Significant positive association between type of junction (roundabout) and crash severity compared to crossroads
	Type of junction	Crash severity / minor-severe, other	↘	r=-0,7116	Significant positive association between type of junction (other) and crash severity compared to crossroads
Barua, 2010, Canada	Type of junction	Crash severity / fatal, crossroad on straight section	↗	r=0,5760, p=0,026, 90% CI	Significant negative association between crossroad on straight section and crash occurrence compared to T-intersection
	Type of junction	Crash severity / fatal, crossroad on curve	-	r=0,7030, p=0,104, 90% CI	Non-significant association between crossroad on curve and crash occurrence compared to T-intersection
	Type of junction	Crash severity / fatal, T-intersection on curve	↗	r=0,662, p=0,078, 90% CI	Significant negative association between T-intersection on curve and crash occurrence compared to T-intersection
	Type of junction	Crash severity / fatal, offset (staggered) intersection	↗	r=2,05, p=0,012, 90% CI	Significant negative association between staggered intersection and crash occurrence compared to T-intersection
Boufous, 2008, Australia	Type of junction	Injury severity / T-intersection or staggered, multiple (>4 arms, non roundabout) and roundabouts	↗	r=0-0,493, p<0,001	Significant negative effect of complex intersections on road safety of older drivers (even though slope Is negative)
Chiou, 2013, Taiwan	Number of legs	Crash severity / All, second party, 3-leg intersection	↗	r=0,172, 90% CI	Significant negative effect of 3-leg intersections on road safety of second party (not at fault)

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Number of legs	Crash severity / All, second party, 4 or more legs intersection	↗	r=0,287, 90% CI	Significant negative effect of 4- or more legged intersections on road safety of second party (not at fault)
	Number of legs	Crash severity / Property damage only, first party, 3-leg intersection	-	e=2,75	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Possible injury, first party, 3-leg intersection	-	e=-0,01	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Evident injury, first party, 3-leg intersection	-	e=-0,01	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Disabling injury and fatality, first party, 3-leg intersection	-	e=-0,02	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Property damage only, first party, 4 or more legs intersection	-	e=3,52	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Possible injury, first party, 4 or more legs intersection	-	e=-0,01	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Evident injury, first party, 4 or more legs intersection	-	e=-0,02	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Disabling injury of fatality, first party, 4 or more legs intersection	-	e=-0,04	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Property damage only, second party, 3-leg intersection	-	e=3,32	Non-significant association between intersection type, party or crash severity

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Number of legs	Crash severity / Possible injury, second party, 3-leg intersection	-	e=0,1	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Evident injury, second party, 3-leg intersection	-	e=0,31	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Disabling injury and fatality, second party, 3-leg intersection	-	e=0,57	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Property damage only, second party, 4 or more legs intersection	-	e=4,68	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Possible injury, second party, 4 or more legs intersection	-	e=0,18	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Evident injury, second party, 4 or more legs intersection	-	e=0,57	Non-significant association between intersection type, party or crash severity
	Number of legs	Crash severity / Disabling injury of fatality, second party, 4 or more legs intersection	-	e=1,16	Non-significant association between intersection type, party or crash severity
Dumbaugh, 2009, United States	Number of 3-leg intersections	Crash count / Severe	-	r=-0,0009, p=0,559	No significant effect of number of 3-legged intersections on severe crashes in road network
	Number of 4-leg intersections	Crash count / Severe	↗	r=0,0068, p=0,0002, 95% CI	Significant negative effect of number of 4-legged intersections on severe crashes in road network
	Number of 3-leg intersections	Crash count / Fatal	↘	r=-0,0073, p=0,073, 90% CI	Significant positive effect of number of 3-legged intersections on fatal crashes in road network

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Number of 4- or more-leg intersections	Crash count / Fatal	↘	r=-0,0099, p=0,095, 90% CI	Significant positive effect of number of 4-legged intersections on fatal crashes in road network
	Number of 3-leg intersections	Crash count / All	-	r=0,0008, p=0,6	No significant effect of number of 3-legged intersections on all crashes in road network
	Number of 4- or more-leg intersections	Crash count / All	↗	r=0,005, p=0,017, 95% CI	Significant negative effect of number of 4-legged intersections on all crashes in road network
Helai, 2008, Singapore	Type of junction	Crash severity / Crossroads	-	r=-0,72, OR=0,07	No significant positive effect of crossroads on accident severity
	Type of junction	Crash severity / T- or Y-intersections	↗	r=0,18, OR=1,2	Significant negative effect of T- or Y-intersections on accident severity
iRAP, 2013, -	Type of junction	Crash count / Unsignalized crossroad, protected turn	-	RR=1,37	Risk of severe car or PTW crash at unsignalized crossroad with protected turn is 37% higher than at T-intersection
	Type of junction	Crash count / Unsignalized crossroad, no protected turn	-	RR=1,6	Risk of severe car or PTW crash at unsignalized crossroad without protected turn is 60% higher than at T-intersection
	Type of junction	Crash count / Signalized crossroad, protected turn	-	RR=1,23	Risk of severe car or PTW crash at signalized crossroad with protected turn is 23% higher than at T-intersection
	Type of junction	Crash count / Signalized crossroad, no protected turn	-	RR=1,39	Risk of severe car or PTW crash at signalized crossroad with protected turn is 39% higher than at T-intersection
Langford, 2006, Australia	Type of junction	Crash severity / Crossroad, 65-74 years	-	Rel.Dif=-1,4	Drivers between 65 and 74 years have 1,4% less crashes at crossroads
	Type of junction	Crash severity / T-arm, 65-74 years	-	Rel.Dif=1,8	Drivers between 65 and 74 years have 1,8% more crashes at t-intersections
	Type of junction	Crash severity / Roundabout, 65-74 years	-	Rel.Dif=-0,5	Drivers between 65 and 74 years have 0,5% less crashes at roundabouts

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Type of junction	Crash severity / Other or unknown, 65-74 years	-	Rel.Dif=-0,1	Drivers between 65 and 74 years have 0,1% less crashes at other or unknown intersections
	Type of junction	Crash severity / Crossroad, 75+ years	-	Rel.Dif=2,2	Drivers older than 75 years have 2,2% more crashes at crossroads
	Type of junction	Crash severity / T-arm, 75+ years	-	Rel.Dif=-2,5	Drivers older than 75 years have 2,5,8% less crashes at t-intersections
	Type of junction	Crash severity / Roundabout, 75+ years	-	Rel.Dif=0,1	Drivers older than 75 years have 0,1% more crashes at roundabouts
	Type of junction	Crash severity / Other or unknown, 75+ years	-	Rel.Dif=0,1	Drivers older than 75 years have 0,1% more crashes at other or unknown intersections
Poch, 1996, United States	Number of legs	Crash count / Angle-accident	↗	r=1,1230	Significant negative effect of number of intersection legs on angle-accident occurrence
Polders, 2014, Belgium	Type of junction	Crash count / T-intersection, rear-end crashes	↗	r=0,3497, OR=1,42, p<0,01	Significant negative effect of T-intersections on the occurrence of rear-end crashes at signalized intersections
Pulugurtha, 2011, United States	Number of legs	Crash count / -	↗	r=0,3872, p=0,09	Significant negative effect of number of intersection legs on road safety of pedestrians
Qin, 2010, United States	Type of junction	Crash count / T-intersection	↘	r=-0,2728, p<0,0001	Significant positive effect of T-intersection on road safety
Schepers, 2011, Netherlands	Type of junction	Crash count / Crossroad, cyclist has right of way crash	-	r=-016, p=1,295	Non-significant positive effect of crossroads compared to T-intersections when it comes to bicycle-motor vehicle crashes and cyclists has right of way
	Type of junction	Crash count / Crossroad, motor vehicle has right of way crash	-	r=0,25, p=0,528	Non-significant negative effect of crossroads compared to single separate bicycle crossing when it comes to bicycle-motor vehicle crashes and motorist has right of way

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Type of junction	Crash count / T-intersection, motor vehicle has right of way crash	-	r=-0,19, p=0,635	Non-significant positive effect of T-intersections compared to single separate bicycle crossing when it comes to bicycle-motor vehicle crashes and motorist has right of way
Tay, 2007, Singapore	Type of junction	Crash severity / Minor injury, Severe injury, Fatal, crossroad	↗	r=0,055, p=0,003	Significant negative association between crossroads and the occurrence of minor, severe of fatal crashes on crossroads compared to T-intersections
	Type of junction	Crash severity / Minor injury, crossroad	-	RR=1	The risk for minor injury crashes is the same for crossroads and T-intersections.
	Type of junction	Crash severity / Severe injury, crossroad	-	RR=1,13	The risk of severe injury crashes is 13% higher on crossroads than on T-intersections.
	Type of junction	Crash severity / Fatal, crossroad	-	RR=1,18	The risk of fatal injury crashes is 18% higher on crossroads than on T-intersections.
	Type of junction	Crash severity / Minor injury, Severe injury, Fatal, Y-intersection	-	r=0,049, p=0,421	Non-significant negative association between Y-intersections and the occurrence of minor, severe of fatal crashes on crossroads compared to T-intersections
	Type of junction	Crash severity / Minor injury, Y-intersection	-	RR=1	The risk for minor injury crashes is the same for Y-intersections and T-intersections.
	Type of junction	Crash severity / Severe injury, Y-intersection	-	RR=1,12	The risk of severe injury crashes is 12% higher on Y-intersection than on T-intersections.
	Type of junction	Crash severity / Fatal, Y-intersection	-	RR=1,16	The risk of fatal injury crashes is 16% higher on Y-intersections than on T-intersections.
Ukkusuri, 2012, Unites States	Type of junction	Crash severity / Severe injury, fatal injury, T-intersection	↘	r=-0,01, 99% CI	Significant positive association between T-intersections and the risk of severe or fatal injury crashes of pedestrians

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Type of junction	Crash severity / Severe injury, fatal injury, crossroad	↗	r=0,03, 99% CI	Significant negative association between crossroads and the risk of severe or fatal injury crashes of pedestrians
	Type of junction	Crash severity / Severe injury, fatal injury, 5-legged intersection	↗	r=0,06, 95% CI	Significant negative association between 5-legged intersections and the risk of severe or fatal injury crashes of pedestrians
	Type of junction	Crash severity / Fatal injury, T-intersection	↘	r=-0,006, 95% CI	Significant positive association between T-intersections and the risk of fatal injury crashes of pedestrians
	Type of junction	Crash severity / Fatal injury, crossroad	-	r=0,028	Non-significant negative association between crossroads and the risk of fatal injury crashes of pedestrians
	Type of junction	Crash severity / Fatal injury, 5-legged intersection	-	r=-0,002	Non-significant negative association between 5-legged intersections and the risk of fatal injury crashes of pedestrians
Wadhwa, 2006, Australia	Type of junction	Fatality rate / Crossroad, signalized	-	0,532%	Percent of fatal crashes
	Type of junction	Fatality rate / Crossroad, signed	-	1,04%	Percent of fatal crashes
	Type of junction	Fatality rate / Crossroad, no control	-	1,05%	Percent of fatal crashes
	Type of junction	Fatality rate / T-intersection, signalized	-	0,438%	Percent of fatal crashes
	Type of junction	Fatality rate / T-intersection, signed	-	0,789%	Percent of fatal crashes
	Type of junction	Fatality rate / T-intersection, no control	-	0,967%	Percent of fatal crashes
	Type of junction	Fatality rate / Roundabout	-	0,191%	Percent of fatal crashes

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
Xie, 2013, China	Type of junction	Crash count / T-intersection	-	r=-0,29	Non-significant positive effect of T-intersections on crash occurrence at urban signalized intersection compared to crossroads
Xu, 2014, China	Number of legs	Crash count / 4 or more legs	↘	r=0,48, p<0,05	Significant positive association between number of legs (4+) and slight injury crash likelihood

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

3.2 FULL LIST OF STUDIES

3.2.1 List of studies

A detailed list of studies coded is presented below:

Abdel-Aty, M. & Wang, X. (2006). Crash Estimation at Signalized Intersections Along Corridors. Transportation Research Record: Journal of the Transportation Research Board, 1953, pp. 98-111.

Anowar, S., & Tay, R. (2014). Factors Influencing the Severity of Intersection Crashes in Bangladesh. Asian Transport Studies, 3, Issue 2.

Barua, U., Azad, A.K., & Tay, R. (2010). Fatality Risk of Intersection Crashes on Rural Undivided Highways in Alberta, Canada. Transportation Research Record, 2148, pp. 107-115.

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Synopsis 32: At-grade junction deficiencies - skewness / junction angle

1 Summary

Soteropoulos, A. & Stadlbauer, S., September 2016

1.1 COLOUR CODE: YELLOW

Most of the studies show that if roads intersect at a skewed angle (not at right angles) there is an increase to the crash risk. These results in most of the cases were statistically significant. However, for specific types of crashes such as rear-end crashes varied effects were observed. Furthermore a skewed angle probably leads to more serious crashes (statistically significant results), however also non-statistically significant opposite effects on accident severity have been reported as well.

1.2 KEYWORDS:

Skewness; junction angle; intersection; junction; degree

1.3 ABSTRACT

Regarding the risk of skewness at an intersection, it can be observed that most studies on accident frequency show that a skewed angle (not at right angles) at intersections leads to a higher crash risk compared to an intersection with road intersecting at right angles (or close to that). Furthermore it also appears that a skewed angle at junctions leads to more serious crashes (i.e. an increase of injury severity) – in most cases the area type was not specifiedResults showing these tendencies were statistically significant in most studies, however a few studies presented varying effects for crash risk for specific crash types, such as rear-end crashes, although mostly not statistically significant. Thus a skewed angle at junctions appears to lead to a higher crash risk and probably to more serious crashes in general.

Age and road user type (truck driver) influence the effect of skewness considerably. For instance skewed intersections can pose problems for older drivers because of their decline in head and neck mobility.

1.4 BACKGROUND

1.4.1 What is skewness?

Skewness is referring to the angle of the crossing roads at an intersection. Often roads at an intersection cross at 90 degrees (vertical or right-angled intersections). If this is not the case, intersections are described as skewed. Thus skewness is mainly a result of environmental factors such as road geometry.

1.4.2 How does the skewness / junction angle affect road safety?

Skewed intersections present a risk factor for road safety as skewed angles between the crossing roads at an intersection can reduce the overview and make simple turning manoeuvers difficult (Elvik et al.2009). Furthermore crossing a skewed-angle intersection may result in blind spots caused by the vehicle body and difficulty in scanning the oncoming traffic (Dong et al. 2014b). This is especially the case for truck drivers in connection with the visibility of pedestrians or other road

users. Thus a skewness angle is likely related to the problem of sight distance (Haghighatpour & Moayedfar 2014).
Moreover vehicles crossing a skewed-angle intersection have a longer distance to traverse while crossing the intersecting roadway, which results in an increased exposure time to the cross oncoming traffic. When making right or left turns at skewed-angle intersections drivers may have more difficulty aligning their vehicles as they turn onto the cross street and (in right turns) may encroach upon lanes intended for oncoming traffic from the right (Dong et al. 2014).

1.4.3 Which safety outcomes are affected by skewness / junction angle?

In the international literature, the effect of skewness / junction angle on road safety has been measured on two basic outcomes, namely accident frequency (number of crashes occurred) and accident severity (severity of injuries of occupants given that an accident has occurred).

1.4.4 How is the effect of skewness studied?

International literature indicated that the effect of skewness at intersections is usually examined by applying multivariable linear statistical models. In the most commonly found accident frequency models, the relationship between skewness / junction angle and number of crashes is investigated with Poisson or negative binomial models. In accident severity models (less commonly investigated), the studies identified applied ordered probit or logistic regression models. The studies identified focused on intersections at urban roads as well as on intersections at rural roads. Most studies focused on motor vehicle crashes (partly specific types of crashes), only one study analysed pedestrian crashes. Most research has been done in the United States but also Japan and Iran.

1.4.5 Which factors influence the effect of skewness on road safety?

Age and road user type (truck driver) seem to have the biggest influences on the effect of skewness. Especially for older drivers skewed intersections pose problems because of their decline in head and neck mobility and the related reduction of their ability to effectively scan to the rear and the side of their vehicle to observe blind spots. Furthermore the restricted motion may be expected to hinder the timely recognition of conflicts during turning and merging manoeuvres at intersections (Ostrow et al. 1992). Moreover intersections with a skewed angle especially reduce the visibility for truck drivers (Haghighatpour & Moayedfar 2014). In addition, the already increased exposure time to cross oncoming traffic for vehicles at a skewed-angle intersection is greater for trucks because of their lower acceleration rates and longer vehicle lengths (Dong et al. 2014a).

1.5 OVERVIEW RESULTS

Most of the studies identified show that a skewed angle appears to have negative effects on road safety. Studies on accident frequency show that a skewed angle at intersections appears to lead to a higher crash risk compared to an intersection angle of 90 or near 90 degrees. Furthermore studies on accident severity indicate that a skewed angle at intersections leads to more serious crashes (i.e. an increase to injury severity). These results were statistically significant in most studies, although results in some studies showed the same tendency but were statistically non-significant. Few studies presented estimates showing different effects between a skewed angle at intersections and the occurrence of specific crash types such as rear-end crashes. However, results for contrary effects were mostly not statistically significant.

Although some studies from Japan or Iran have been identified, the potential transferability of results is questionable, due to the fact that the vast majority of studies has been conducted in the United States and is maybe linked with national specifications.

However, in general, a skewed angle at intersections appears to lead to a higher crash risk and to more serious crashes in general, although for some crash types heterogenous effects tend to appear. Since there was no meta-analysis obtained during the literature search the conclusions are based on the studies presented in the reference list.

1.6 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound. However some of the studies used only small samples for investigation.

Overall, the topic has not been very deeply studied (number of relevant studies is 12). Especially only some research was done regarding accident severity. Furthermore the studies identified concerned mostly crashes with motor vehicles and often did not differentiate between road user groups. Moreover research was mostly carried out in the United States – no European studies found - and is probably linked with national specifications. However there was consistency of results, the majority of most studies identified that a skewed angle at intersections appears to lead to a higher crash risk and to more serious crashes.

2 Scientific overview

2.1 RESULTS

Most of the studies identified that a skewed angle appears to have negative effects on road safety. Studies on accident frequency (the most commonly found) mostly show that a skewed angle at intersections leads to a higher crash risk compared to an intersection angle of 90 or near 90 degrees. Two studies (Dong et al. 2014a; Dong et al. 2014b) show a significant positive association between junction angle (up to 90°) and motor vehicle-crashes (car-, car-truck- and truck-crashes), meaning that the more skewed the angle of the intersection the higher the risk for motor vehicle crashes. Dong et al. (2014c) indicates that this is the case for the occurrence of crashes of all severities (fatal, incapacitating injury, non-incapacitating injury, possible injury, property damage injury). Furthermore estimates presented by Wang et al. (1999) show that an angle of the entering approach and the left-turn approach of an intersection (right-hand traffic) lower than 75° or higher than 105° (defined as skew) increases the likelihood of rear-end crashes statistically significant. Moreover Wang and Nihan (2001) indicate a statistically significant rise of the probability of encountering an obstacle vehicle at skewed intersections and therefore a higher risk of angle-crashes. However for rear-end crashes (Kim et al. 2007) a positive effect of skewness (lower crash risk) has been observed, although not statistically significant. For pedestrians the results of Haghighatpur and Moayedfar (2014) indicate that 90°-intersections have a significant positive effect (lower crash risk) on road safety for pedestrians, meaning that skewed intersections show an elevated crash risk.

Studies on accident severity indicate that a skewed angle at intersections leads to more serious crashes (i.e. an increase to injury severity). Results of Haleem et al. (2010) – was the only study on accident severity with statistically significant results, this – show that a skewed intersection angle (less than or equal 75°) statistically significant increases fatal injury probability. Results of Barua et al. 2010 also show a positive (increasing) effect of skewed intersections on fatal accident occurrence, but these results were not statistically significant though.

Table 1 illustrates the results of the vote-count analysis. Results show that skewed intersections (clearly more or less than 90°) tend to lead to more crashes than rectangular intersections. When it comes to accident severity similar results occurred but the total number of effects was rather small.

Table 1 Results of the vote-count analysis

	Total number of effects tested	**Result (number of effects)***				**Result (% of effects)**	
		↗	-	↘		↗	↘
Accident Frequency**	**22**	**5**	**4**	**13**		**28%**	**72%**
skewed (clearly > or < 90°)	10	5	4	1		83%	17%
rectangular (up to 90°)	12	0	0	12		0%	100%
Accident Severity**	**3**	**1**	**2**	**0**		**100%**	**0%**

skewed (clearly > or < 90°)	3	1	2	0		100%	0%
rectangular (up to 90°)	-	-	-	-		-	-

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)
**Since exposures differ, the summarized effects for accident frequency and accident severity can't be interpreted as main results.

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

Overall 12 high quality studies on skewness / junction angle were selected and coded. Most of the studies (10) focused on accident frequency and 2 studies (Barua et al. 2010; Haleem and Abdel-aty 2010) focused on accident severity. In order to examine the relationship between skewness / junction angle and outcome indicators, all studies deployed multivariable statistical models (i.e. negative binomial, Poisson, logistic, etc.) as a method of examining the topic and controlled for other geometrical characteristics and traffic flow as well.

Studies on accident frequency used mostly negative binomial regression (Dong et al. 2014b; Haghighatpour and Moayedfar 2014; Kumara and Weerakoon 2003; Wang et al. 1999; Wang and Nihan 2001) or poisson (Dong et al. 2014a; Dong et al. 2014c) models. In the two studies on accident severity logistic regression models and binary probit models were developed.

The studies identified focused on intersections at urban roads as well as on intersections at rural roads. Most studies focused on motor vehicle crashes (partly specific types of crashes). Only one study (Haghighatpour and Moayedfar 2014) analysed pedestrian crashes. Most research has been done in the United States. Overall 6 studies were carried out there. But also Japan (2 studies), Iran (2 studies), Canada (1 study) and Singapore (1 study) were part of the examination.

Table 2 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 2 Description of coded studies

Author, Year, Country	**Sample, method/design and analysis**		**Reference group**	**Additional information on analysis**
Barua, 2010, Canada	Observational, logistic regression model, data of 3544 crashes, 2003-2005	Regression analysis between intersection characteristics and crash severity	T-intersections on straight section	Road network was limited to rural roads, focus on fatal crashes
Burchett, 2005, United States	Crash data analysis of 200 rural expressway intersections, 1996-2000,	-	-	Focus on highway crossings
Dong, 2014a, United States	Observational, case-control, unmatched, Poisson-lognormal regression model, 245 signalized intersections and 6790 crashes between 2005 and 2009	Regression analysis between intersection characteristics and crash occurrence	-	Road network was limited to urban roads
Dong, 2014b, United States	Observational, case-control, unmatched , multivariate random-parameters zero-inflated negative binomial (MRZINB)	Regression analysis between intersection	-	Road network was limited to urban roads

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
	regression model, 3015 intersections and 7840 crashes between 2001 and 2005	characteristics and crash occurrence		
Dong, 2014c, United States	Observational, multivariate zero-inflated Poisson (MZIP) regression model, crash data from the Tennessee Roadway Information System (2005-2009)	Regression between intersection characteristics and crash occurrence	-	Focus on accident severity
Haghighatpour, 2014, Iran	Observational, negative binomial model, 16 signalized intersections, 2012-2013	Regression between intersection characteristics and crash occurrence	Other than 90°	Road network was limited to urban roads, focus on pedestrian crashes
Haleem, 2010, United States	Observational, binary probit model, crash data of 2043 intersections between 2003 und 2006	Regression analysis between intersection characteristics and crash severity	Intersections with angle >75°	Focus on severe injuries
Kim, 2007, United States	Observational, Case-control, unmatched, binomial multilevel model, data of 91 intersection and 548 crashes, 1996-1997	Regression analysis between intersection characteristics and crash occurrence	Intersections with 90°	Road network was limited to rural roads, focus on crash type
Kumara, 2003, Singapore	Observational, negative binomial model, unmatched case-control including three-legged intersections (n=104) between 1992 and 2000	Regression analysis between intersection characteristics and crash frequency	Intersections with approach angle <=90°	Road network was limited to urban roads
Monajjem, 2013, Iran	Experimental, model for accident prediction by the use of IHSDM software,	Analyse and evaluation of safety performance of highway geometrical design effects	-	Road network was limited to rural roads
Wang, 1999, Japan	Observational, negative binomial model, 116 intersections with 1105 observations, 1992-1995	Regression analysis between intersection characteristics and crash occurrence	Within angle of 75° and 105° or -15° and 15°	Road network was limited to urban roads, focus in rear-end crashes
Wang, 2001, Japan	Observational, negative binomial model, 81 signalized intersections,	Regression analysis between intersection characteristics and crash occurrence	Within certain angle	Road network was limited to urban roads, focus on accident with crossing vehicle

2.3 CONCLUSION

Studies on the effect of skewness / junction angle on road safety identified in the international literature mostly focused on accident frequency, although also some studies on accident severity were found.

Nearly all studies on accident frequency show that a skewed angle of an intersections leads to a higher crash risk compared to an intersection angle of 90 or near 90 degrees. These results in most of the cases were statistically significant. Whereas most studies indicate these effects for motor vehicles, one study – focussing on pedestrians – also indicate similar results for pedestrians. However for specific types of crashes such as rear-end crashes varibale effects were observed. Whereas Kim et al. (2007) found a non-significant positive effect of skewness on the occurrence of rear-end crashes, Wang et al. (1999) mentioned a significant negative (increasing) effect of intersection geometry.

Only two studies on accident severity were identified, with only one of which had statistically significant results. This study shows that a skewed intersection angle (less than or equal 75°) statistically significant increases fatal injury probability, thus appears to lead to more serious crashes. However non-statistically significant results from another study on accident severity showed opposite effects.

In general a skewed angle appears to lead to a higher crash risk and probably tend to lead to more serious crashes (i.e. an increase to injury severity). Thus a skewed angle at intersection appears to have negative effects on road safety. However, it should be noted that there is some variability between findings of different studies.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

Literature search was conducted in March and April 2016. It was carried out in four databases with similar search strategies. Following databases were browsed through during the literature search: 'Scopus', 'Science Direct', 'TRID' and 'Taylor and Francis Online'. Detailed search terms, as well as their linkage with logical operators and combined queries are shown in the following tables. The study scope did not exclude countries or source types like "Journal" or "Project". In some of the searches remaining studies were limited to subject areas (e.g. "Engineering"). Out of the overall 601 potentially eligible studies, after screening the abstracts of these 601 studies from only 74 the full-text were obtained and only 6 were coded and included in the synopsis. Other already known or during the literature search occasionally (e.g. via Google) found studies as well as studies found in the literature search for other topics and including effects for skewness / junction angle were added as additional studies (6). The reference lists of the studies were only partly checked.

Table 3 Literature search strategy, database: Scopus

search no.	search terms / operators / combined queries	hits
#1	(TITLE-ABS-KEY ("skewness" OR "skew" OR "angle" OR "risk") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	**18,686**
#2	TITLE-ABS-KEY ("skewness" OR "skew" OR "regression" OR "angle" AND "risk" OR "crash") AND TITLE-ABS-KEY ("intersection" OR "junction") AND PUBYEAR > 1989	**992**
#3	(TITLE-ABS-KEY ("skew" OR "angle" AND "crash" OR "risk") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	**351**
#4	(TITLE-ABS-KEY ("skew" OR "angle" OR "crash" AND "regression") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989 AND (LIMIT-TO (SUBJAREA , "ENGI"))	**173**

Table 4 Literature search strategy, database: ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	pub-date > 1989 and "skewness" OR "skew" OR "angle" AND "risk" AND "intersection" OR "junction"	**34.459**
#2	pub-date > 1989 and "skewness" OR "skew" OR "angle" AND "risk" AND "intersection" OR "junction" [All Sources(Engineering, Social Sciences)].	**6.707**
#3	pub-date > 1989 and TITLE-ABSTR-KEY("skew" OR "angle" OR "crash" OR "risk" AND "regression" OR "correlation") and TITLE-ABSTR-KEY("intersection" OR "junction")[All Sources(Engineering,Social Sciences)]	**146**

Table 5 Literature search strategy, database: TRID

search no.	search terms / operators / combined queries	hits
#1	"junction" OR "intersection" AND "skew" OR "angle" AND "risk" OR "crash" Sources (Highways, Pedestrians and Bicyclists, Safety and Human Factors, Transportation (General)	**15.000**
#2	"skew" OR "angle" AND "risk" OR "crash" AND TITLE ("junction" OR "intersection") Sources (Highways, Pedestrians and Bicyclists, Safety and Human Factors, Transportation (General)	**340**
#3	"skew" OR "angle" AND "crash" OR "risk" AND TITLE ("junction" OR "intersection") Sources (Highways, Pedestrians and Bicyclists, Safety and Human Factors, Transportation (General)	**188**

Table 6 Literature search strategy, database: Taylor & Francis Online

search no.	search terms / operators / combined queries	hits
#1	"junction" OR "intersection" AND "skew" OR "angle" AND "risk" OR "crash"	**3541**
#2	"skew" OR "angle" AND "crash" AND ABSTRACT ("intersection")	**94**

Table 7 Results Literature Search

Database	**Hits**
Scopus (remaining papers after several limitations/exclusions)	173
ScienceDirect	146
TRID	188
Taylor & Francis Online	94
Total number of studies to screen title/ abstract	**601**

The final 12 studies included in the synopsis indicate that the topic has not been very thoroughly investigated. The prioritizing criteria were the following:

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

No “grey” literature was examined.

No meta-analyses were found.

3.1.2 Exploratory analysis of results

Table 8 presents information on the main outcomes of coded studies on skewness / junction angle.

Table 8 Main outcomes of coded studies for skewness / junction angle

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
Barua, 2010, Canada	Skewness	Crash severity / fatal, skewed crossroad	-	r-0,215, p=0,681	Non-significant positive effect of skewed crossroads on fatal accident occurrence compared to T-intersections
	Skewness	Crash severity / fatal, skewed T-intersection	-	r-1,187, p=0,29	Non-significant positive effect of skewed T-intersections on fatal accident occurrence compared to T-intersections
Burchett, 2005, United States	Skewness	Severity and fatality rate	-	-	Authors mentioned a negative effect of skewed intersections on fatality and severity rates compared to tangent intersections. No estimates presented.
Dong, 2014a, United States	Junction angle	Crash count / Car-crashes	↘	r= -0,002, 95% CI	Significant positive association between junction angle (up to 90°) and car-crashes
	Junction angle	Crash count / Car-truck crashes	↘	r= -0,006, 95% CI	Significant positive association between junction angle (up to 90°) and car-truck-crashes
	Junction angle	Crash count / Truck-crashes	↘	r= -0,022, 95% CI	Significant positive association between junction angle (up to 90°) and truck-crashes
Dong, 2014b, United States	Junction angle	Crash count / Car-crashes	↘	r= -0,07, 95% CI	Significant positive association between junction angle (up to 90°) and car-crashes
	Junction angle	Crash count / Car-truck crashes	↘	r= -0,121, 95% CI	Significant positive association between junction angle (up to 90°) and car-truck-crashes
	Junction angle	Crash count / Truck-crashes	↘	r= -0,179, 95% CI	Significant positive association between junction angle (up to 90°) and truck-crashes
Dong, 2014c, United States	Junction angle	Crash count / fatal	↘	r=-0,031, 95% CI	Significant positive association between junction angle (up to 90°) and fatal crashes
	Junction angle	Crash count / incapacitating injury	↘	r=-0,035, 95% CI	Significant positive association between junction angle (up to 90°) and incapacitating injury crashes
	Junction angle	Crash count / non-incapacitating injury	↘	r=-0,024, 95% CI	Significant positive association between junction angle (up to 90°) and non-incapacitating injury crashes

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Junction angle	Crash count / possible injury	↘	r=-0,009, 95% CI	Significant positive association between junction angle (up to 90°) and possible injury crashes
	Junction angle	Crash count / property damage only	↘	r=-0,011, 95% CI	Significant positive association between junction angle (up to 90°) and property damage only crashes
Haghighatpour, 2014, Iran	Junction angle	Crash count / 90°	↘	r=0,071, p= 0,014	Even though coefficient is negative, 90°-intersections have a significant positive effect on road safety for pedestrians
Haleem, 2010, United States	Junction angle	Injury severity / intersections with angle <=75°	↗	r=0,3183 , p=0,0069	Significant negative association between intersection angle <=75° and crash severity
Kim, 2007, United States	Skewness	Crash count / Angle crash	-	r=0,228	Non-significant negative effect of skewness on occurrence of angle crashes
	Skewness	Crash count / Rear-end crash	-	r=-0,650	Non-significant positive effect of skewness on occurrence of rear-end crashes
	Skewness	Crash count / Sideswipe crash (same direction)	↗	r=0,901, 90% CI	Significant negative effect of skewness on occurrence of sideswipe crashes (same direction)
	Skewness	Crash count / Sideswipe crash (opposite direction)	-	r=-1,114	Non-significant negative effect of skewness on occurrence of sideswipe crashes (opposite direction)
Kumara, 2003, Singapore	Skewness	Accident frequency / T-intersection	-	r=-0,3052	Non-significant positive effect of skewness of intersection approach on road safety at T-intersections
Monajjem, 2013, Iran	Junction angle	Crash count / 90°, 565m curve radius, simple circle curve	-	3,41	3,41 crashes per km on the road
	Junction angle	Crash count / 100°, 565m curve radius, simple circle curve	-	3,41	3,41 crashes per km on the road
	Junction angle	Crash count / 110°, 565m curve radius, simple circle curve	-	3,41	3,41 crashes per km on the road
	Junction angle	Crash count / 120°, 565m curve radius, simple circle curve	-	3,41	3,41 crashes per km on the road
	Junction angle	Crash count / 130°, 565m curve radius, simple circle curve	-	3,42	3,42 crashes per km on the road

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Junction angle	Crash count / 140°, 565m curve radius, simple circle curve	-	3,42	3,42 crashes per km on the road
	Junction angle	Crash count / 150°, 565m curve radius, simple circle curve	-	3,42	3,42 crashes per km on the road
	Junction angle	Crash count / 160°, 565m curve radius, simple circle curve	-	3,42	3,42 crashes per km on the road
	Junction angle	Crash count / 90°, 716m curve radius, simple circle curve	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 100°, 716m curve radius, simple circle curve	-	3,4	3,4 crashes per km on the road
	Junction angle	Crash count / 110°, 716m curve radius, simple circle curve	-	3,4	3,4 crashes per km on the road
	Junction angle	Crash count / 120°, 716m curve radius, simple circle curve	-	3,4	3,4 crashes per km on the road
	Junction angle	Crash count / 130°, 716m curve radius, simple circle curve	-	3,4	3,4 crashes per km on the road
	Junction angle	Crash count / 140°, 716m curve radius, simple circle curve	-	3,4	3,4 crashes per km on the road
	Junction angle	Crash count / 150°, 716m curve radius, simple circle curve	-	3,41	3,41 crashes per km on the road
	Junction angle	Crash count / 160°, 716m curve radius, simple circle curve	-	3,41	3,41 crashes per km on the road
	Junction angle	Crash count / 90°, 565m curve radius, clothoid-circle-clothoid curve, 60m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 100°, 565m curve radius, clothoid-circle-clothoid curve, 60m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 110°, 565m curve radius, clothoid-circle-clothoid curve, 60m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 120°, 565m curve radius, clothoid-circle-clothoid curve, 60m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 130°, 565m curve radius, clothoid-circle-clothoid curve, 60m clothoid length	-	3,39	3,39 crashes per km on the road

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Junction angle	Crash count / 140°, 565m curve radius, clothoid-circle-clothoid curve, 60m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 150°, 565m curve radius, clothoid-circle-clothoid curve, 60m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 160°, 565m curve radius, clothoid-circle-clothoid curve, 60m clothoid length	-	3,38	3,38 crashes per km on the road
	Junction angle	Crash count / 90°, 565m curve radius, clothoid-circle-clothoid curve, 85m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 100°, 565m curve radius, clothoid-circle-clothoid curve, 85m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 110°, 565m curve radius, clothoid-circle-clothoid curve, 85m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 120°, 565m curve radius, clothoid-circle-clothoid curve, 85m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 130°, 565m curve radius, clothoid-circle-clothoid curve, 85m clothoid length	-	3,39	3,39 crashes per km on the road
	Junction angle	Crash count / 140°, 565m curve radius, clothoid-circle-clothoid curve, 85m clothoid length	-	3,38	3,38 crashes per km on the road
	Junction angle	Crash count / 150°, 565m curve radius, clothoid-circle-clothoid curve, 85m clothoid length	-	3,38	3,38 crashes per km on the road
	Junction angle	Crash count / 160°, 565m curve radius, clothoid-circle-clothoid curve, 85m clothoid length	-	3,37	3,37 crashes per km on the road
	Junction angle	Crash count / 90°, 565m curve radius, clothoid-circle-clothoid curve, 115m clothoid length	-	3,38	3,38 crashes per km on the road
	Junction angle	Crash count / 100°, 565m curve radius, clothoid-circle-clothoid curve, 115m clothoid length	-	3,38	3,38 crashes per km on the road
	Junction angle	Crash count / 110°, 565m curve radius, clothoid-circle-clothoid curve, 115m clothoid length	-	3,38	3,38 crashes per km on the road
	Junction angle	Crash count / 120°, 565m curve radius, clothoid-circle-clothoid curve, 115m clothoid length	-	3,38	3,38 crashes per km on the road

Author, Year, Country	**Exposure variable**	**Outcome variable / Outcome type**	**Effects**		**Main outcome - description**
	Junction angle	Crash count / 130°, 565m curve radius, clothoid-circle-clothoid curve, 115m clothoid length	-	3,38	3,38 crashes per km on the road
	Junction angle	Crash count / 140°, 565m curve radius, clothoid-circle-clothoid curve, 115m clothoid length	-	3,38	3,38 crashes per km on the road
	Junction angle	Crash count / 150°, 565m curve radius, clothoid-circle-clothoid curve, 115m clothoid length	-	3,38	3,38 crashes per km on the road
	Junction angle	Crash count / 160°, 565m curve radius, clothoid-circle-clothoid curve, 115m clothoid length	-	3,37	3,37 crashes per km on the road
Wang, 1999, Japan	Angle of entering approach and left-turn approach	Crash count / Other than within 75° and 105°	↗	r=0,294, 85% CI	Significant negative effect of skewed intersections on occurrence of rear-end crashes
	Angle of entering approach and opposite approach	Crash count / Other than within -15° and 15°	↗	r=0,211, 85% CI	Significant negative effect of skewed intersections on occurrence of rear-end crashes
Wang, 2001, Japan	Angle of entering approach and opposite approach	Crash count / Other than within +/-30°	↘	r= -1,451, 85% CI	Significant reduction of probability of through-vehicle driver's reaction failure at skewed intersections
	Angle of entering approach and opposite approach	Crash count / Other than within +/-15°	↗	r= 0,329, 85% CI	Significant rise of probability of encountering an obstacle vehicle at skewed intersections
	Angle of opposite approach and right approach	Crash count / Other than within 75° and 105°	↗	r= 0,273, 85% CI	Significant rise of probability of encountering an obstacle vehicle at skewed intersections

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

3.2 FULL LIST OF STUDIES

3.2.1 List of studies

A detailed list of studies coded is presented below:

Barua, U., Azad, A.K., & Tay, R. (2010). Fatality Risk of Intersection Crashes on Rural Undivided Highways in Alberta, Canada. Transportation Research Record, 2148, pp. 107-115.

Burchett, G.D., & Maze, T.H. (2005). Rural Expressway Intersection Characteristics that Contribute to Reduced Safety Performance. Proceedings of the 2005 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 2005.

Dong, C., Clarke, D.B., Richards, S.H., & Huang, B. (2014a). Differences in passenger car and large truck involved crash frequencies at urban signalized intersections: An exploratory analysis. Accident Analysis and Prevention, 62, pp. 87-94.

Dong, C., Clarke, D.B., Yan, X., Khattak, A., & Huang, B. (2014b). Multivariate random-parameters zero-inflated negative binomialregression model: An application to estimate crash frequenciesat intersections.Accident Analysis and Prevention, 70, pp. 320-329.

Dong, C., Richards, S.H., Clarke, D.B., Zhou, X., & Ma, Z. (2014c). Examining signalized intersection crash frequency using multivariate zero-inflated Poisson regression. Safety Science, 70, pp. 63-69.

Haghighatpour, P.J., & Moayedfar, R. (2014). Pedestrian Crash Prediction Models and Validation of Effective Factors on Their Safety (Case Study: Tehran Signalized Intersections). Open Journal of Civil Engineering 2014, 4, pp. 240-254.

Haleem, K., & Abdel-Aty, M. (2010). Examining traffic crash injury severity at unsignalized intersections. Journal of Safety Research, 41, pp. 347-357.

Kim, D., Lee, Y., Washington, S., & Choi, K. (2007). Modeling crash outcome probabilities at rural intersections: Application of hierarchical binomial logistic models. Accident Analysis and Prevention, 39, pp. 125-134.

Kumara, S.S.P., Weerakoon W.M.S.B. (2003). Identification of Accident Causal Factors and Prediction of Hazardousness of Intersection Approaches. TRB 2003 Annual Meeting.

Monajjem, M.S., Kamali, M.H.J., & Ayubirad, M.S. (2013). Studying the effect of spiral curves and intersection angle, on the accident rates in two-lane rural highways in Iran. Promet – Traffic&Transportation, 25, 343-348.

Wang, Y., Ieda, H., Saito, K., & Takahashi, K. (1999). Using Accident Observations to evaluate rear end accident risk at four-legged signalized intersections. Safety Analysis and Policy, Paper n°268.

Wang, Y., & Nihan, N.L. (2001). Quantitative Analysis on Angle-Accident Risk at Signalized Intersections. Safety Analysis and Policy.

3.2.2 References on further background information

Elvik, R. / Høye, A. / Vaa, T. / Sørensen, M. (2009): The Handbook of Road Safety Measures. Second edition. Emerald Group. Bingley

Ostrow, A.C. / Shaffron, P. / McPherson, K. (1992): The effects pf a joint range-of-motion physical fitness training program on the automobile driving skills of older adults. Journal of Safety Research, 23, 207 – 219.

Synopsis 33: At-grade junctions deficiencies - poor sight distance

1 Summary

Soteropoulos, A. & Stadlbauer, S., September 2016

1.1 COLOUR CODE: YELLOW

Most of the studies on (poor) sight distance at junctions show an elevated crash risk. For example the restriction of field of view leads to more crashes. At the same time some of the estimates are not statistically significant and furthermore two studies delivered contrary results, which showed that decreased sight distance may decrease crash occurrence. Despite those, it can be concluded that poor sight distance is probably risky.

1.2 KEYWORDS

Sight distance; visual restriction; accident frequency; junction;

1.3 ABSTRACT

Poor sight distance at junctions can affect road safety, as it results in other road users and/or obstacles not being detected soon enough for the driver to safely stop the vehicle. Hence, an adequate field of view is of great importance, especially when operating speeds are high. Though it is unclear if and how (poor) sight distance influences the crash risk at junctions. Most of the studies show a correlation between restricted sight distance and crash occurrence but only a few of them delivered significant results. At the same time two studies showed very interesting contrary estimates, which might be due to higher speeds chosen when there is a better view provided – increases in the sight distances may allow drivers to have greater freedom of manoeuvre. The main approach used to investigate the relationship between sight distance and crash risk was regression analyses. Sight distance was often one factor considered as part of investigations considering a range of factors which influence road safety. One study used a driving simulator rather than real driving approach. Most research was done in Singapore but also in the United States and China. The majority of the studies investigated junctions on urban roads.

1.4 BACKGROUND

1.4.1 What is (poor) sight distance?

Poor sight distance or sight-distance restriction is most common at stop-controlled or uncontrolled junction approaches due to: fixed objects in medians or at the junction corners, sight-restricting horizontal or vertical curvature of the roadway, or overgrown brush or other vegetation. In cases like these, a (sight distance) restriction arises when the standard sight line based on the speed of traffic on the crossing street is not provided from the stop point on the approach to cross traffic in both ways. Sight distance restriction may occur at signalised junctions because of horizontal or vertical curvature across the junction, an object in a median area, or misaligned left turn lanes (Poch & Mannering, 1996).

Poor sight distance is mainly a result of environmental factors, such as road geometry, vegetation etc. and has no direct connection to drivers' characteristics (age, gender etc.).

1.4.2 How does (poor) sight distance affect road safety?

Short sight distances may put drivers in a critical condition and reduce the driver's ability to judge the traffic condition at a junction (Kumara & Weerakoon, 2003). With regard to horizontal curvature, gradient or an object in the median, a (sight distance) restriction arises when the largest identifiable gap in oncoming traffic is not adequate to provide the left-turning vehicle time to identify the gap and complete the left-turning manoeuvre. In general, regardless of the cause, sight distance restrictions have negative effects, these include: a reduction in the amount of time road users have to identify and react to traffic control devices and regulatory signs. Hence, poor sight distance or restrictions can lead to an increase in accident frequency (Poch & Mannering, 1996).

It must be emphasised that different experimental methods or differences in the road network or locations can lead to different results. As Chin & Quddus (2003) and Mitra & Quddus (2002) showed, a better field of view can in certain circumstances increase the number of crashes, because operating speeds at junctions with clearer sighting distance are often higher. Besides speed, also the average daily traffic volume influences accident frequency at junctions with poor sight distance.

1.4.3 Which safety outcomes are affected by (poor) sight distance?

In the international literature, the effect of (poor) sight distance on road safety has been measured mainly on one outcome, namely the accident frequency (number of crashes occurred).

1.4.4 How is the effect of (poor) sight distance studied?

International literature indicated that the effect of (poor) sight distance at junctions is usually examined by applying multivariable linear statistical models. In the majority of accident frequency models, the relationship between (poor) sight distance and number of crashes is investigated with negative binomial models – those studies compared the crash rates of junctions or crashes at junctions with specific characteristics (e.g. specific sight distance) with other junctions. A less common approach (only used in one of the coded studies) was a driving simulator where junctions with different sight distances had to be driven by participants. Most studies focused on junctions on urban roads and most research has been done in Singapore, but also in the United States and China. Only the driving simulator considered both private and professional drivers – some of the participants were taxi drivers – however results were not presented separately.

1.4.5 Which factors influence the effect of poor sight distance on road safety?

The operating speed and the traffic volume have the biggest influences on the effect of poor sight distance on road safety. Even though speed is not directly considered along with sight distance in most of the studies, it is obvious that the combination of both higher speeds and poorer sight distance can produce higher numbers of crashes. However, better fields of view can also lead to drivers choosing higher speeds which in itself can lead to higher accident frequencies. Furthermore it is obvious that the higher the Average Daily Traffic (ADT) at a junction, the more crashes occur. Age, gender, personality, stress etc. seem not to influence the effect of poor sight distance. Although they may lead to other driver behaviour factors e.g. higher driving speeds but do not influence crash frequencies directly.

1.5 OVERVIEW RESULTS

Most of the studies show that poor sight distance leads to a higher crash risk, in terms of accident frequency, compared to a better field of view. However, effects are often statistically non-significant. Furthermore two studies presented significant estimates which show a greater number of crashes occurring at junctions with good sight distance (contrary estimates).

There is some suggestion, factors that could influence the effect of poor sight distance at junctions include: speed limit, average daily traffic volume, weather. Personal factors such as the driver's age might also influence the crash risk due to differences in driving behaviour between age groups. The studies did not investigate if there was any connection between those factors, and only the driving simulator study set a specific speed limit for the participants.

1.6 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound. However some of the studies used only small samples for investigation.

Overall, the topic has not been deeply studied (number of relevant studies is 7). It is interesting that research only focused on accident frequency, no studies identified focused on accident severity. Furthermore the studies identified concerned mostly crashes with motor vehicles and often did not differentiate between road user groups. Moreover research was mostly carried out in Singapore – no European studies were found. Findings are probably influenced by national specifications.

2 Scientific overview

2.1 RESULTS

Most of the studies identified show that poor sight distance leads to a higher crash risk compared to a better field of view. Poch and Mannering (1996) indicate that the presence of a sight distance restriction (due to different reasons) significantly increases accident frequency (r=1,123). This was also shown for specific types of crashes such as rear-end crashes when there was restricted sight distance for left-turning vehicles due to a fixed object (r=2,312). Restricted sight distance on a stop-controlled approach significantly increased the risk of angle-crashes (r=1,621) and a restricted field of view leads to a significantly higher approach-turn-accident risk (1,764).

If sight distance at signalized T-junctions is greater than 100m Kumara and Weerakoon (2003) indicated that crash occurrence is lower when compared to junctions with a poorer sight distance (r=-0.4377). Kumara and Chin (2003) showed similar results (r=-0,2347 and r=-0,1433). Accident frequency seems to decrease when sight distance is greater than 100m. But it has to be noticed that the last two studies didn't present significant results when it comes to poor sight distance.

Further also results presented in the iRAP fact sheet indicated that the likelihood of crash is 42% higher at junctions with poor sight distance for different road users (cars, PTWs, pedestrians and cyclists), however there is no information provided about data and methods.

Yan and Weng (2016) investigated the crash risks at junctions with different field of view (IFOV) conditions. For IFOV1 the lengths of clear sight triangle legs are 80m on major roads and 70m on minor roads. Based on this condition, the junction angles of IFOV2 and IFOV3 conditions were increased by 5° (Yan and Weng, 2016). When the IFOV1 condition is compared to IFOV2 or IFOV3 the crash rate decreased by 57,3% and 76,5%, respectively (Yan and Weng, 2016). These results show that the crash risk can be effectively reduced by improving drivers' IFOV.

It is interesting that two studies (Chin and Quddus 2003; Mitra and Quddus 2002) present significant estimates which show a positive correlation between crash occurrence and sight distance (contrary estimates).This may seem surprising but in these studies junction sight distances ranges from 65m to 400m and for this range, increases in the sight distances may allow drivers to have greater freedom of manoeuvre and may increase their vehicle speeds thus resulting in possibly greater accident frequencies and severity risks (Chin and Quddus 2003). The authors identified a clearly significant estimate (r=0,0006 and p=0.0017) and Mitra and Quddus (2002) presented similar results (r=0,0011 and p=0.021).
Therefore – as described before – it must be emphasised that different methods or differences in the road network or locations may lead to different results.

Table 1 illustrates the results of the vote-count analysis. Results show that poor or restricted sight distance leads to more crashes occurring, whereas adequate sight distance can reduce the number of crashes.

Table 1 Results of the vote-count analysis

	Total number of effects tested	Result (number of effects)*			Result (% of effects)	
		↗	-	↘	↗	↘
Accident Frequency**	15	6	7	2	75%	25%
sight distance restricted	9	4	5	0	100%	0%
sight distance adequate	3	0	2	1	0%	100%
sight distance (in meters)	3	2	0	1	67%	33%

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)
**Since exposures differ, the summarized effects for accident frequency can't be interpreted as main results.

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

Overall 6 high quality studies as well as one additional iRAP factsheet on (poor) sight distance were selected and coded. Most of the studies (Chin and Quddus 2003; Kumara and Weerakoon 2003; Kumara and Chin 2003; Mitra et al. 2002; Poch and Mannering 1996) focused on accident frequency on real roads. In order to examine the relationship between (poor) sight distance and outcome indicators, nearly all studies deployed negative binomial regression models as a method of examining the topic and controlled for other geometrical characteristics and traffic flow as well. Only in one study (Yan et al. 2016) a driving simulator was used, where junctions with different sight distances had to be traversed by the participants.

The studies identified mostly focused on junctions on urban roads. Most studies focused on motor vehicle crashes or crashes between motor vehicles and cyclists or pedestrians respectively. Most research has been done in Singapore. Overall 4 studies were carried out there. But also in the United States (1 study), China (1 study) and Canada (1 study).

Table 2 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 2 Description of coded studies

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Chin, 2003, Singpapore	random effect negative binomial model, cross-sectional design (n=52) for signalized crossroads with 832 observations between 1992 and 1999	Regression analysis between junction characteristics and crash occurrence	-	Road network was limited to urban roads
iRAP, 2013, -	Factsheet, risk factors with regard to motorised vehicles, no details among method or data	Relative risks for: - Pedestrians - Cyclists - PTW - Car drivers	Junctions with adequate sight distance	Risk of collision with cars or PTW, cyclists or pedestrians are presented.

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Kumara, 2003a, Singapore	negative binomial model, unmatched case-control including three-legged junctions (n=104) between 1992 and 2000	Regression analysis between junction characteristics and crash frequency	Junctions with sight distance <= 100m	Road network was limited to urban roads, focus on T-junctions
Kumara, 2003b, Singapore	negative binomial model and zero-inflated negative binomial model, unmatched case-control including three-legged junctions (n=104) between 1992 and 2000	Regression between junction characteristics and crash occurrence	Junctions with sight distance >= 100m	Road network was limited to urban roads, focus in T-junctions
Mitra, 2002, Singapore	zero-inflated negative binomial model and zero-inflated Poisson model, observational design including signalized crossroads (n=52) with 832 observations between 1992 and 1999	Regression analysis between junction characteristics and crash occurrence	-	Road network was limited to urban roads
Poch, 1996, United States	negative binomial model, observational design including junctions (n=63) with 1396 crashes between 1987 and 1993	Regression analysis between junction characteristics and crash occurrence	-	Road network was limited to urban roads
Yan, 2016, China	Driving simulation, 45 persons (24 men / 21 women; 23 professional drivers / 22 unprofessional drivers), 30-40 years, pre-crash driving at junctions under three junction field of view (IFOV) condition	Regression analysis and correlations between field of view and crash rate	IFOV 1: basic ISD requirement for unsignalized junctions	Road network was limited to rural roads

2.3 CONCLUSION

Studies on the effect of (poor) sight distance on road safety identified in the international literature all focused on accident frequency and deployed negative binomial regression models as a method of examining the topic.

Most of the studies show that poor sight distance leads to a higher crash risk compared to a better field of view. However, presented effects are often statistically non-significant (only one study with statistically significant results). Furthermore two studies presented significant estimates which show a positive (increasing) correlation between crash occurrence and sight distance, demonstrating that crash rate can increase with improved sight distance.

Summarizing, there is some evidence to suggest that poor sight distance might lead to a higher crash risk as most studies indicate an elevated risk estimate. However, it should be noted that many presented results were non-significant. Furthermore, two studies indicated that greater sight distance increased accident risk, meaning that clear evidence of the risk factor's effectiveness cannot be provided.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

Literature search was conducted in March and April 2016. It was carried out in four databases with similar search strategies. Following databases were browsed through during the literature search: 'Scopus', 'Science Direct', 'TRID' and 'Taylor and Francis Online'. Detailed search terms, as well as their linkage with logical operators and combined queries are shown in the following tables. The study scope did not exclude countries or source types like "Journal" or "Project". In some of the searches remaining studies were limited to subject areas (e.g. "Engineering"). Out of the overall 518 potentially eligible studies after screening the abstracts of these 518 studies from only 47 the full-text were obtained and only 3 were coded and included in the synopsis. Other already known or during the literature search occasionally (e.g. via Google) found studies as well as studies found in the literature search for other topics and including effects for (poor) sight distance were added as additional studies (4). The reference lists of the studies were only partly checked.

Table 3 Literature search strategy, database: Scopus

search no.	search terms / operators / combined queries	hits
#1	TITLE-ABS-KEY ("sight" OR "visual" OR "crash" OR "risk") AND TITLE-ABS-KEY ("intersection" OR "junction") AND PUBYEAR > 1989	**15,524**
#2	TITLE-ABS-KEY ("sight" OR "visual" AND "crash" OR "risk") AND TITLE-ABS-KEY ("intersection" OR "junction") AND PUBYEAR > 1989 AND (LIMIT-TO (SUBJAREA , "ENGI"))	**104**

Table 4 Literature search strategy, database: ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	pub-date > 1989 and ("intersection" OR "junction" AND "sight" OR "visual" AND "crash" OR "risk")[All Sources(Engineering,Social Sciences)]	**6.558**
#2	pub-date > 1989 and ("sight" OR "visual" AND "crash" OR "risk") and TITLE-ABSTR-KEY("intersection" OR "junction")[All Sources(Engineering,Social Sciences)]	**543**
#3	pub-date > 1989 and ("sight" OR "visual" AND "crash" OR "risk") and TITLE("intersection" OR "junction")[All Sources(Engineering,Social Sciences)	**147**

Table 5 Literature search strategy, database: TRID

search no.	search terms / operators / combined queries	hits
#1	"junction" OR "intersection" AND "sight" OR "view" OR "visual" AND "crash" OR "risk" Sources(Highways, Pedestrians and Bicyclists, Safety and Human Factors, Transportation (General))	**15.000**
#2	"sight" OR "view" OR "visual" AND "crash" OR "risk" AND TITLE ("junction" OR "intersection") Sources(Highways, Pedestrians and Bicyclists, Safety and Human Factors, Transportation (General))	**260**
#3	"sight" OR "view" AND "crash" OR "risk" AND TITLE ("junction" OR "intersection") Sources(Highways, Pedestrians and Bicyclists, Safety and Human Factors, Transportation (General))	**237**

Table 6 Literature search strategy, database: Taylor & Francis Online

search no.	search terms / operators / combined queries	hits
#1	"sight" OR "view" AND "crash" AND ABSTRACT ("intersection")	**347**
#2	"sight" AND "crash" AND ABSTRACT ("intersection" OR "junction")	**30**

Table 7 Results Literature Search

Database	Hits
Scopus (remaining papers after several limitations/exclusions)	104
ScienceDirect	147
TRID	237
Taylor & Francis Online	30
Total number of studies to screen title/ abstract	**518**

The final 7 studies included in the synopsis indicate that the topic has not been thoroughly investigated. The prioritizing criteria were the following:

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

No meta-analyses were found.

3.1.2 Exploratory analysis of results

Table 8 presents an overview of the main outcomes of the coded studies.

Table 8 Main outcomes of coded studies for (poor) sight distance

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome -description
Chin, 2003, Singpapore	Sight distance	Crash count / All	↗	r=0,0006, p=0,0017	Significant negative association between sight distance and crash occurrence at signalized crossroads (e.g. this might be due to higher speeds)
iRAP, 2013, -	Poor sight distance	Crash count / PTW, Car	-	RR=1,42	Likelihood of crash is 42% higher at junctions with poor sight distance for PTW and cars
	Poor sight distance	Crash count / Pedestrian	-	RR=1,42	Likelihood of crash is 42% higher at junctions with poor sight distance pedestrians
	Poor sight distance	Crash count / Cyclist	-	RR=1,42	Likelihood of crash is 42% higher at junctions with poor sight distance for cyclists
Kumara & Weerakoon, 2003, Singapore	Sight distance	Crash frequency / T-junction	-	r=-0,4377, p=0,1330	sight distance greater than 100 meters reduces crash frequency in an non-significant way at T-junctions

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome -description
Kumara & Chin, 2003, Singapore	Sight distance restriction	Crash count / T-junction - negative binomial model	-	r=-0,2347, p=0,1435	sight distance greater than 100 meters reduces crash occurrence in an non-significant way at T-junctions
	Sight distance restriction	Crash count / T-junction – zero inflated negative binomial model	-	r=-0,1433 , p=0,2123	sight distance smaller than 100 meters increases crash occurrence in an non-significant way at T-junctions
Mitra, 2002, Singapore	Sight distance	Crash count / All	↗	r=0,0011, p= 0,021	Significant negative association between sight distance and crash likelihood at signalized crossroads (e.g. this might be due to higher speeds)
Poch, 1996, United States	Sight distance restriction	Crash count / All	↗	r=1,123	Restricted sight distance leads to a significant increase of all crash types
	Sight distance restriction for left-turning vehicles	Crash count / Rear-End	↗	r=2,312	Restricted sight distances for left-turning vehicles leads to a significant increase of rear-end crashes.
	Sight distance restriction on stop-controlled approach	Crash count / Angle-accident	↗	r=1,621	Restricted sight distance on stop-controlled approach leads to a significant increase of angle-crashes.
	Sight distance restriction	Crash count / Approach-Turn	↗	r=1,764	Restricted sight distance leads to a significant increase of approach-turn crashes.
Yan, 2016, China	IFOV condition	Crash rate / IFOV 2	-	r=-0,852, p=0,054	IFOV 2 leads to a non-significant crash reduction compared to IFOV 1.
	IFOV condition	Crash rate / IFOV 3	↘	r=-1,45, p=0,481	The widest field of view (IFOV 3) leads to a significant crash reduction compared to IFOV 1.
	IFOV condition	Crash rate / All	↘	c=-0,284	Significant correlation between junction field of view and road safety

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

3.2 FULL LIST OF STUDIES

3.2.1 List of studies

A detailed list of studies coded is presented below:

Chin, H.C. & Quddus, M.A. (2003). Applying the random effect negative binomial model to examine traffic accident occurrence at signalized. Accident Analysis and Prevention, 35, pp. 253–259.

iRAP (2013). iRAP Road Attribute Risk Factors. Sight Distance. Restriction. International Road Assessment Programme (iRAP).

Kumara, S.S.P. & Weerakoon, W.M.S.B. (2003). Identification of Accident Causal Factors and Prediction of Hazardousness of Intersection Approaches. TRB 2003 Annual Meeting.

Kumara, S.S.P. & Chin, H.C. (2003). Modeling Accident Occurrence at Signalized Tee Intersections with Special Emphasis on Excess. Traffic Injury Prevention, 4, pp. 53-57.

Mitra, S. & Quddus M. (2002). Study of Intersection Accidents by Maneuver Type. Transportation Research Record, 1784, Paper No. 02-3436.

Poch, M. & Mannering, F. (1996). Negative Binomial Analysis of Intersection-Accident Frequencies. Journal of Transportation Engineering March/April 1996.

Yang, X. & Weng, J. (2016): Effects of intersection field of view on emergent collision avoidance performance at unsignalized intersections: Analysis based on driving simulator experiments. Journal of advanced Transportation March 2016.

Synopsis 34: At-grade junction deficiencies - gradient

1 Summary

Soteropoulos, A. & Stadlbauer, S., September 2016

1.1 COLOUR CODE: YELLOW

Effects of gradients at junctions with regards to accident frequency (crash risk) are somewhat variable. However, studies on accident severity indicated that junctions with gradient increase the risk of more severe crashes (i.e. an increase to injury severity) in general. At the same time gradients at junctions appear to only increase the crash risk for specific crash types (especially rear-end crashes).

1.2 KEYWORDS

Gradient; junction; junction; grade; slope; road safety; risk

1.3 ABSTRACT

Regarding the effect of gradient at junctions on road safety, studies on accident frequency show partly variable effects of gradients on crash risk. While some studies on accident frequency indicated that junctions with gradient increase crash risk compared to junctions without gradient for specific crash types (particularly rear-end accident frequency), some studies also showed some contrary results. Studies on accident severity indicated that junctions with gradient increase the risk for more severe crashes, with this being the case for downhill approaches (high-speed crashes) as well as uphill approaches. In summary, gradients at junctions appear to only increase crash risk for specific crash types (especially rear-end crashes), but they tend to lead to more severe crashes (i.e. an increase to injury severity) in general.

1.4 BACKGROUND

1.4.1 What is gradient?

The gradient at an junction describes the longitudinal gradient of (the legs of) the junction (Robinson and Thagesen 2004). It is mainly a result of environmental factors, such as topography and road geometry.

1.4.2 How does gradient affect road safety?

When approaching an junction, steep gradients can reduce visibility and make it difficult to stop or start again after having stopped (Elvik et al.2009). At junctions with a steep downhill gradient, approaching vehicles require greater braking distances in the event of a change in a traffic signal to red or for a conflict with an opposing right-turner (Corben 1990). This difficulty to stop at junctions with a steep downhill gradient is especially high in bad weather conditions (e.g. rain or ice) where vehicles might skid into the junction (Wilson and Lipinski 2004)

In contrast, at junctions with an uphill gradient, drivers of through-vehicles may be more inclined to enter the junction late for a traffic signal which is changing to red, as there are greater time and cost penalties in returning the vehicle to its original speed, once the green phase is re-introduced (Corben 1990).

Furthermore steep gradients at junction approaches lead to less stable speed and poor sight angle of the right-turning vehicles (Wang and Nihan 2001). While the former is the case for gradients in general (possible affection of driver speed and distance judgements), the latter is especially the case for junctions with uphill gradients (Corben 1990). Moreover steep gradients at junctions make it difficult especially for heavy vehicles to accelerate at reasonable rates within the vicinity of the junction (Robinson and Thagesen 2004).

1.4.3 Which safety outcomes are affected by gradient?

In the international literature, the effect of gradient on road safety has been measured on two basic outcomes, namely accident frequency (number of crashes occurred) and accident severity (severity of occupants' injuries given that an accident has occurred).

1.4.4 How is the effect of gradient studied?

International literature indicated that the effect of gradient at junctions is usually examined by applying multivariable linear statistical models. In the most commonly found accident frequency models, the relationship between gradient and number of crashes is investigated mostly with negative binomial models. In accident severity models, the studies identified mostly applied logistic regression models. The studies mostly focused on junctions on urban roads. In nearly all studies the focus was on motor vehicles and most research has been undertaken in the United States, Canada and Singapore.

1.5 OVERVIEW RESULTS

With regards to the effects of gradient at junctions on road safety, studies on accident frequency show partly variable effects of gradients on crash risk, whereas studies on accident severity indicated that junctions with gradient increase the risk for more severe crashes. Gradients at junctions supposable only increase crash risk for specific crash types (especially rear-end crashes). Another study indicated a significant positive effect of gradient on the occurrence of sideswipe crashes (opposite direction) as well as for angle-crashes and also rear-end crashes. However, results were not statistically significant for the latter.

In one study it was found out that accident occurrence at T-junctions may be reduced when there is a gradient between 5 to 8%, which is surprising.

However gradients tend to lead to more severe crashes (i.e. an increase to injury severity) in general. Also the risk for higher casualty crashes increases by the occurrence of a slope. For instance junctions located at a (constant) grade are associated with a high(er) fatality risk, which can be described by the higher speeds chosen when driving. Also cyclists approaching junctions with downhill grade have a significantly increased risk for injury when compared to level junctions.

1.6 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound. However some of the studies used only small samples for investigation and in one study also mitigation factors such as signing and markings at the gradients influencing the results are described.

Overall, the topic has not been deeply studied (number of relevant studies is 8). Research mainly focused on crashes with motor vehicles – only one study focused on bicycles. Moreover research was mostly carried out in the United States, Canada and Singapore, with no European studies found, findings are probably influenced by national specifications.

2 Scientific overview

2.1 RESULTS

Regarding the effects of gradient at junctions on road safety, studies on accident frequency show partly variable effects of gradients for crash risk, whereas studies on accident severity indicated that junctions with gradient increase the risk for more severe crashes.

Some studies on accident frequency indicated that junctions with gradient increase crash risk compared to junctions without gradient for specific crash types. Results of Poch and Mannering (1996), for example, indicate that an uphill or downhill gradient greater than 5% at junctions significantly increases rear-end accident frequency. In addition Wang and Nihan (2001) – setting the probability of encountering an obstacle vehicle (a turning vehicle which gets suddenly stopped from completing the intended movement because of an appearing pedestrian/bicyclist) as variable affecting the risk of an angle-accident – indicate a significant negative effect of gradient on the opposite approach on crash occurrence. Hence the probability of encountering an obstacle vehicle (right-turning vehicle interrupting the smooth movement of opposing through vehicles when turning) increases and therefore a higher risk for angle-crashes occurs. Furthermore, Kim et al. (2007) indicate a negative effect of gradient on the occurrence of sideswipe crashes in the same direction, although this effect was not statistically significant.

However the studies on accident frequency also partly showed contrary estimates. Kim et al. (2007), for example, also indicate a significant positive effect of gradient on the occurrence of sideswipe crashes (opposite direction). The same results were presented for angle crashes and rear-end crashes as well, however not statistically significant. Furthermore Kumara and Weerakoon (2003) show that gradients on junction approaches exceeding 5% (but below 8%) may reduce accident occurrence at T-junctions. This is considered surprising from the authors but it is explained that all junctions considered had gradients less than 8% and thus it is concluded that although grades exceeding 8% are known to be more hazardous, grades from 5-8% may be safer than level roads. Also results of Kumara and Chin (2003) indicate that approaches on gradients of 5% or more may significantly reduce accident occurrence. However the same explanation as described before is used for explaining this surprising result. Moreover it is described that there likely are mitigation factors such as signing and markings at these gradients. Furthermore, in addition to their indication of a significant increase of rear-end accident frequency for a greater than 5% uphill or downhill gradient at junctions, Poch and Mannering (1996) also indicated that a greater than 5% uphill or downhill grade at junctions decreases angle accident frequency.

Studies on accident severity indicate that junctions with gradient increase the risk for higher casualty crashes. Barua et al. (2010) indicates that junctions located at a (constant) grade are associated with high (respectively higher) fatality risk (compared with level junctions/ junctions not located at a grade). This is – as described in the study – because drivers tend to drive at a higher speed down to the grade and these high-speed crashes tend to increase the likelihood of fatality at junctions located at grades. Furthermore results of Corben (1990) indicate that the gradient on the opposing approach prior to the junction has a significant negative effect on injury severity (higher casualty accident frequencies). For the gradient on the opposing approach at the junction also a negative effect on injury severity is shown, however this effect was not statistically significant. Moreover it is summarized that higher casualty accident frequencies tend to be associated more with uphill rather than downhill opposing approaches, prior to and at the junctions. In addition, results of Harris et al. (2013) – referring to bicyclists – indicated that bicyclists approaching junctions with downhill grades (downhill route grade) significantly increased injury risk compared with level junctions (flat route grade).

Table 1 gives an overview over the results of the vote-count analysis. Regarding accident frequency the vote-count analysis shows no clear results for gradients at junctions. But gradients tend to lead to more severe crashes (increase in injury severity) in general.

Table 1 Results of the vote-count analysis

	Total number of effects tested	Result (number of effects)				Result (% of effects)	
		↗	-	↘		↗	↘
Accident Frequency	**11**	**3**	**4**	**4**		**43%**	**57%**
urban	7	3	1	3		50%	50%
rural	4	0	3	1		0	100%
Accident Severity	**3**	**2**	**1**	**0**		**100%**	**0%**
urban	0	0	0	0		-	-
rural	1	1	0	0		100%	0%

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

Overall 8 high quality studies on gradient were selected and coded. 5 studies focused on accident frequency (Kim et al. 2007; Kumara and Weerakoon 2003; Kumara and Chin 2003; Poch and Mannering 1996; Wang and Nihan 2001) and 3 studies (Barua et al. 2010; Corben 1990; Harris et al. 2013) focused on accident severity. In order to examine the relationship between gradient and outcome indicators, all studies deployed multivariable statistical models (i.e. negative binomial, logistic regression etc.) as a method of examining the topic and controlled for other geometrical characteristics and traffic flow as well.

Studies on accident frequency deployed negative binomial models (4) or binomial multilevel models (1). One of these studies (Wang and Nihan 2001) set the probability of encountering an obstacle vehicle as variable affecting the risk of an angle-accident. Studies on accident severity mostly deployed logistic regression models.

The studies identified mostly focused on junctions on urban roads; only 2 studies (Barua et al. 2010; Kim et al. 2007) focused on junctions on rural roads. In nearly all studies the focus was on motor vehicles; only 1 study (Harris et al. 2013) focused on bicycles. Most research has been undertaken in the United States (2 studies), Canada (2 studies) and Singapore (2 studies). But also Japan (1 study) and Australia (1 study) were part of the examination.

Table 2 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 2 Description of coded studies

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Barua, 2010, Canada	Observational, logistic regression model, data of 3544 crashes, 2003-2005	Regression analysis between junction characteristics and crash frequency	Level junction	Road network was limited to rural roads, focus on fatal crashes
Corben, 1990, Australia	Observational, linear regression model, data of 53 signalized junctions, 1982-1986	Regression analysis between junction characteristics and crash frequency	No gradient	Focus on injury crashes
Harris, 2013, Canada	Observational, Case-control, Crossover/Repeated-measures, multiple logistic regression models, 210 junctions, 2008-2009,	Regression analysis between junction characteristics and crash occurrence	272 control sites (level)	Road network was limited to urban roads, focus on cyclists (older than 18 years) and non-fatal crashes
Kim, 2007, United States	Observational, Case-control, unmatched, binomial multilevel model, data of 91 junction and 548 crashes, 1996-1997	Regression analysis between junction characteristics and crash occurrence	Level junctions	Road network was limited to rural roads, focus on crash type
Kumara, 2003a, Singapore	Observational, negative binomial model, unmatched case-control including T-junctions (n=104) between 1992 and 2000	Regression analysis between junction characteristics and crash frequency	Junctions with gradient <=5%	Road network was limited to urban roads
Kumara, 2003b, Singapore	negative binomial model and zero-inflated negative binomial model, unmatched case-control including three-legged junctions (n=104) between 1992 and 2000	Regression between junction characteristics and crash occurrence	Junctions with gradient <=5%	Road network was limited to urban roads, focus in T-junctions
Poch, 1996, United States	negative binomial model, observational design including junctions (n=63) with 1396 crashes between 1987 and 1993	Regression analysis between junction characteristics and crash occurrence	-	Road network was limited to urban roads
Wang, 2001, Japan	Observational, negative binomial model, 81 signalized junctions,	Regression analysis between junction characteristics and crash occurrence	Junctions within +/- 3% gradient	Road network was limited to urban roads, focus on accident with crossing vehicle

2.3 CONCLUSION

Studies on the effect of gradient on road safety identified in the international literature focused on accident frequency as well as on accident severity.

The results of the studies on accident frequency are somewhat variable. Whereas some studies on accident frequency indicated indeed that junctions with gradient increase crash risk compared to junctions without gradient at least for specific crash types (especially the case for rear-end accident frequency), some studies partly also showed contrary results.

Studies on accident severity indicated though that junctions with gradient increase the risk for more severe crashes and this is the case for downhill approaches (high-speed crashes) and uphill approaches.

In summary, gradients at junctions tend to lead to more severe crashes (i.e. an increase to injury severity). Regarding crash risk, gradients at junctions appear only to increase crash risk for specific crash types, especially rear-end crashes, although partly heterogenous effects were presented.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

Literature search was conducted in March and April 2016. It was carried out in four databases with similar search strategies. The following databases were browsed through during the literature search: 'Scopus', 'Science Direct', 'TRID' and 'Taylor and Francis Online'. Detailed search terms, as well as their linkage with logical operators and combined queries are shown in the following tables. The study scope did not exclude countries or source types like "Journal" or "Project". In some of the searches remaining studies were limited to subject areas (e.g. "Engineering"). Out of the overall 445 (mostly unique) potentially eligible studies, after screening the abstracts only 58 of the full-texts were obtained and only 4 were coded and included in the synopsis. Additionally 5 studies were identified during the literature search occasionally (e.g. via Google), were already known or were found in the literature search for other topics. The reference lists of the studies were only partly checked.

Table 3 Literature search strategy, database: Scopus

search no.	search terms / operators / combined queries	hits
#1	(TITLE-ABS-KEY ("gradient" OR "slope" OR "risk" OR "crash" OR "regression") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	18.754
#2	(TITLE-ABS-KEY ("gradient" OR "risk" OR "crash" AND "regression") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989 AND (LIMIT-TO (SUBJAREA , "ENGI"))	210

Table 4 Literature search strategy, database: ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	pub-date > 1989 and "Gradient" AND "intersection" OR "Regression" OR "Crash"	211.279
#2	pub-date > 1989 and "Gradient" And "intersection" AND "Crash"	626
#3	pub-date > 1989 and "Gradient" and "intersection" and "Crash"[All Sources(Engineering,Environmental Science,Psychology,Social Sciences)].	311
#4	pub-date > 1989 and "Gradient" and "intersection" and "Crash" and "Regression"	168
#5	pub-date > 1989 and "Gradient" and "intersection" and "Crash" and "risk"[All Sources(Engineering,Environmental Science,Psychology,Social Sciences)]	141

Table 5 Literature search strategy, database: TRID

search no.	search terms / operators / combined queries	hits
#1	"gradient" OR "intersection" OR "crash"	15.000
#2	"gradient" OR "slope" AND "intersection" AND "crash"	1.922
#3	"gradient" AND "intersection" and "crash"	6

Table 6 Literature search strategy, database: Taylor & Francis Online

search no.	search terms / operators / combined queries	hits
#1	"gradient" AND "intersection" and "crash"	86

Table 7 Results Literature Search

Database	**Hits**
Scopus (remaining papers after several limitations/exclusions)	210
ScienceDirect	141
TRID	6
Taylor & Francis Online	84
Additional studies	4
Total number of studies to screen title/ abstract	**445**

The final 8 studies included in the synopsis indicate that the topic has not yet been thoroughly investigated in general. Studies selected to code were prioritized as followed:

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

No meta-analyses were found.

3.1.2 Exploratory analysis of results

Table 8 presents information on the main outcomes of coded studies on gradient.

Table 8 Main outcomes of coded studies on gradient

Author, Year, Country	**Exposure variable**	**Outcome variable / Outcome type**	**Effects**		**Main outcome -description**
Barua, 2010, Canada	Gradient	Crash severity / fatal, grade	↗	r=0,565, p=0,084, 90% CI	Significant negative effect of gradient on fatal accident occurrence
Corben, 1990, Australia	Gradient	Crash severity / gradient on opposing approach at the junction	-	r=0,2725, p=0,0506	Non-significant negative effect of gradient at junction on injury severity
	Gradient	Crash severity / gradient on opposing approach prior to junction	↗	r=0,9195, p=0,0178	Significant negative effect of gradient prior to junction on injury severity
Harris, 2013, Canada	Gradient	Injury count / Downhill route grade (<= -1°) at junction	↗	OR=2,22, 95% CI	Significant negative association between downhill route grade and injury risk at junctions
Kim, 2007, United States	Gradient	Crash count / horizontal curves, angle crashes	-	r=-0,1310	Non-significant positive effect of gradient on occurrence of angle crashes

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome -description
	Gradient	Crash count / horizontal curves, rear-end crashes	-	r=-0,027	Non-significant positive effect of gradient on occurrence of rear-end crashes
	Gradient	Crash count / horizontal curves, sideswipe crashes (same direction)	-	r=0,1510	Non-significant negative effect of gradient on occurrence of sideswipe crashes (same direction)
	Gradient	Crash count / horizontal curves, sideswipe crashes (opposite direction)	↘	r=-1,144, 99% CI	Significant positive effect of gradient on occurrence of sideswipe crashes (opposite direction)
Kumara, 2003a, Singapore	Gradient	Accident frequency / >5%	-	r= -0,314, p=0,181	Non-significant positive association between gradient and crash frequency at T-junctions
Kumara & Chin, 2003, Singapore	Gradient	Crash count / T-junction - negative binomial model	↘	r=-0,4509, p=0,0006	Significant positive effect of gradient at T-junction on crash occurrence
	Gradient	Crash count / T-junction – zero inflated negative binomial model	↘	r=-0,3028, p=0,0032	Significant positive effect of gradient at T-junction on crash occurrence
Poch, 1996, United States	Gradient on approach	Crash count / greater than 5% uphill or downhill gradient, rear-end crashes	↗	r=0,454	Significant negative effect of 5% uphill or downhill gradient on occurrence of rear-end crashes
	Gradient on approach	Crash count / greater than 5% uphill or downhill gradient, angle crashes	↘	r=-0,251	Significant positive effect of 5% uphill or downhill gradient on occurrence of angle crashes
Wang, 2001, Japan	Gradient on opposite approach	Crash count / encountering an obstacle vehicle	↗	r= 0,308, 85% CI	Significant negative effect of gradient on opposite approach on probability of encountering on an obstacle vehicle

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

3.2 FULL LIST OF STUDIES

3.2.1 List of studies

A detailed list of the coded studies is presented below:

Barua, U., Azad, A.K., & Tay, R. (2010). Fatality Risk of Intersection Crashes on Rural Undivided Highways in Alberta, Canada. Transportation Research Record, 2148, pp. 107-115.

Corben, B.F., & Wai, F.C. (1990). Pro-active Traffic Engineering Safety Study. Final Report, Part 2: Right-Turn-Against Crashes at Traffic Signals. Monash University Accident Research Centre - Report #13.

Harris, M.A., Reynolds, C.C.O., Winters, M., Cripton P.A., Shen, H., Chipman M.L., Cusimano M.D., Babul S., Brubacher J.R., Friedman S.M., Hunter G., Monro M., Vernich L., & Teschke, K. (2013). Comparing the effects of infrastructure on bicycling injury at intersections and non-intersections using a case–crossover design. Injury Prevention 2013, 19, pp. 303-310.

Kim, D., Lee, Y., Washington, S., & Choi, K. (2007). Modeling crash outcome probabilities at rural intersections: Application of hierarchical binomial logistic models. Accident Analysis and Prevention, 39, pp. 125-134.

Kumara, S.S.P., & Weerakoon, W.M.S.B. (2003). Identification of Accident Causal Factors and Prediction of Hazardousness of Intersection Approaches. TRB 2003 Annual Meeting.

Kumara, S.S.P., & Chin, H.C. (2003). Modelling Accident Occurence at Signalized Tee Intersections with Special Emphasis on Excess Zeros. Traffic Injury Prevention, 4, Issue 1, pp. 53-57.

Poch, M., & Mannering, F. (1996). Negative Binomial Analysis of Intersection-accident frequencies. Journal of Transportation Engineering March/April 1996.

Wang, Y., & Nihan, N. (2001). Quantitative Analysis on Angle-Accident Risk at Signalized Intersections. Safety Analysis and Policy.

3.2.2 References on further background information

Elvik, R. / Høye, A. / Vaa, T. / Sørensen, M. (2009): The Handbook of Road Safety Measures. Second edition. Emerald Group. Bingley

Robinson, R. / Thagesen, B. (2004): Road Engineering for Development. Second Edition. Spon Press. London, New York.

Wilson, E.M. / Lipinksi M.E. (2004): National Cooperative Highway Research Program Sythesis 336. Road Saftey Audits. A Systhesis of Highway Practice. Transportation Research Board. Washington D.C.

Synopsis 35: Uncontrolled rail-road crossing

1 Summary

Soteropoulos, A. & Stadlbauer, S., September 2016

1.1 COLOUR CODE: YELLOW

In general it can be summarised that uncontrolled rail-road crossings tend to have a higher crash risk compared to rail-road crossings equipped with (active) control devices. Thus, rail-road crossings with active control devices have positive effects on road safety. Furthermore partly also variable effects are presented.

1.2 KEYWORDS

Rail-road crossings; uncontrolled; risk; level crossing, railway level crossing, grade crossing

1.3 ABSTRACT

From the studies identified in the international literature it appears that uncontrolled/passive rail-road crossings are associated with a higher crash risk compared to rail-road crossings equipped with active control devices. Also the risk for a more severe injury crash at uncontrolled/passive rail-road crossings is higher than at rail-road crossings with active warning devices. Further the studies identified partly show variable effects and also national specifications regarding the different control types which play a role for the effects estimated in the studies as well.

1.4 BACKGROUND

1.4.1 What is an uncontrolled rail-road crossing?

The term of uncontrolled rail-road crossings mainly refers to rail-road crossings equipped only with a sign indicating the level crossing presence (crossbucks). Passive level crossings often have a sign indicating the level crossing presence augmented with either a stop sign or give way sign for traffic control. The only traffic control devices provided to road users are fixed signs which do not alter when a train is present. This is in contrast to active crossings which have control devices or warning systems such as gates, barriers (with flashing lights) or flashing lights alone etc. which indicate that a train is approaching. (Raub 2009).

1.4.2 How does an uncontrolled rail-road crossing affect road safety?

Uncontrolled rail-road crossings or rail-road crossings with passive warning devices provide less safe conditions for drivers traversing the level crossings compared to rail-road crossings equipped with active warning devices. This is because at uncontrolled or passive rail-road crossings road users must rely only on their perception of whether a train is approaching in order to determine if it is safe to traverse, whereas rail-road crossings with active warning devices provide other optical and/or acoustical warnings or even physical barriers to prevent a crossing (Wullems et al. 2013). In addition, it is possible that equipping rail-road crossings with stop signs only may increase crash risk due to the commonality of stop signs and the subsequent desensitization of motorists to the sign requirements (Austin and Carson 2002).

However, at rail-road crossings equipped with active warning devices, road users tend to rely on the warning signals rather than or instead of looking for approaching rail vehicles (Wullems et al. 2013).

1.4.3 Which safety outcomes are affected by uncontrolled rail-road crossings?

In the international literature, the effect/risk of uncontrolled rail-road crossings on road safety has been measured on two basic outcomes, namely accident frequency (number of crashes occurred) and (less often) accident severity (severity of injuries of occupants given that an accident has occurred).

1.4.4 How is the effect of uncontrolled rail-road crossings studied?

The effect of uncontrolled rail-road crossings is often examined by applying multivariable linear statistical models. In the most commonly found accident frequency models, the relationship between different types of control devices (passive or no control devices, and active devices) and number of crashes is investigated with Poisson or negative binomial models. This was often done by comparing the crash risk at rail-road crossings with passive warning devices (e.g. stop sign only) with the crash risk at rail-road crossings with specific active warning devices. In accident severity models, the studies identified applied ordered probit or logistic regression models. Moreover some studies only undertook a crash data analysis and calculated crash rates for different grade crossing types (passive/no control device and active control device).

1.5 OVERVIEW RESULTS

The results of the literature found shows that uncontrolled/passive rail-road crossings tend to have a higher crash risk compared to rail-road crossings equipped with active control devices. Thus, it can be summarised that rail-road crossings with active control devices have positive effects on road safety. Additionally, also the crash severity is affected by the control type of crossing. A few studies indicate that the risk for a more severe injury crash at uncontrolled/passive rail-road crossings is higher than at rail-road crossings with active warning devices. Further the studies identified partly show variable effects. They partly present contrary estimates: e.g. a statistically significant association of rail-road crossings with stop signs with a lower frequency of rail-road crossing crashes (compared with rail-road crossings without stop signs) or a significantly decrease of accident likelihood by crossbucks only and no control device compared with stop sign warning device only. In addition, it must be emphasized, that an uncontrolled/passive high-road crossing (i.e. the signs used e.g. crossbuck only or stop sign only) differ due to national specifications which also have consequences for the effects (in part different crash risk for rail-road crossing with crossbucks or stop signs only) estimated.

1.6 NOTES ON ANALYSIS METHODS

In general, most coded studies are of sufficient quality and are methodologically sound. However it must be emphasized that some studies only undertook crash data analyses and calculated crash rates for different rail-road crossing types (passive/no control device and active control device).

Overall, the topic has not been deeply studied (number of relevant studies is 9). Especially only some research was done regarding accident severity. Moreover research was mostly carried out in the United States – no European studies found – and is probably linked with national specifications. Especially for this topic these national specifications are relevant because warning devices at rail-road crossings differ between countries. For example in Europe (e.g. in Austria or Germany) it is more common that rail-road crossings are at least equipped with a crossbuck-sign, whereas in the United States rail-road crossing are equipped with stop signs only. It is differences in design requirements like these which have consequences for the effects estimated in the different studies regarding the crash risk for uncontrolled rail-road crossings.

2 Scientific overview

2.1 RESULTS

From the studies identified in the international literature it appears that uncontrolled/passive rail-road crossings are associated with a higher crash risk compared to rail-road crossings equipped with active control devices. Furthermore some studies identified partly variable effects (rail-road crossings without a sign had a significantly lower accident likelihood compared with crossings with stop sign warning device) and in addition it must be emphasized, that an uncontrolled/passive rail-road crossing (i.e. the signs used e.g. crossbuck only or stop sign only) differ between studies due to national specifications which has also consequences for the effects estimated.

Studies on accident frequency mostly show a significantly lower crash risk for rail-road crossings with active control devices compared to uncontrolled rail-road crossings. Nam and Lee (2006) for example indicate that crash risk at rail-road crossings with (active) warning / control devices is significantly lower (r=-0,818) compared to rail-road crossings with no (active) control devices, indicating a higher crash risk for uncontrolled rail-road crossings. Results of Austin and Carson (2002) – using the probable presence of different warning devices (probability of a particular warning device - i.e. gate - being present at a crossing) amongst others as variables for their accident prediction model – indicated that the probable presence of gates and highway traffic signals (active warning devices) significantly reduce highway-rail crossing accident frequency (r= -2,974). In line with this the probable presence of stop signs (only) at rail-road crossing was found to increase predicted accident frequency. Results of Lu and Tolliver (2016) also indicate that compared with stop sign warning device only, active warning devices like gates and flashing lights decrease accident likelihood significantly. Again this indicates a higher crash risk for uncontrolled rail-road crossings. In addition, results presented in the iRAP fact sheet indicated that the crash risk at uncontrolled/passive rail-road crossings for cars/PTWs or cyclists is twice or three times as high compared with a rail-road crossing with active warning devices, although there is no further information about data and methods provided.

However, within the same studies partly contrary estimates were also presented. Nam and Lee (2006) indicated that rail-road crossings with stop signs present were statistically significantly associated with a lower frequency of rail-road crossing crashes compared to rail-road crossings without stop signs (not clarified if no signs at all or active crossing) and explained this by the fact, that the presence of a stop sign could lead to a lower vehicle traveling speed, creating a lower likelihood for crashes on rail-road crossings. Further results of Lu and Tolliver (2016) also show that crossbuck signs only and also no control device (no sign) are associated with a significantly lower accident likelihood compared with stop sign warning device only. These interesting results might occur because the higher reported crash frequency at active crossings is an artefact of greater traffic flow (AADT) at these crossings.

In addition results of Austin and Carson (2002) also indicate that flashing lights or bells increase predicted accident frequency. The authors suggest that this might be due to the fact that the active nature of flashing lights may encourage motorists to cross before the train arrives (i.e. beating the train, after the lights have started) and may on occasion malfunction and therefore motorists more likely disregard the flashing lights. Moreover results of Yan et al. (2010) show that crossings with railroad advance warning signs (in addition to crossbucks) have a higher crash frequency, while those without railroad advance warning signs (crossbuck only) have a lower crash frequency; however this results was not statistically significant.

The two studies on accident frequency which only undertook a crash data analysis and calculated crash rates for different rail-road crossing types (Anandarao 1998; Raub 2009) also indicate higher crash rates for uncontrolled rail-road crossings, however heterogenous effects are also presented. Using Data from all highway-rail grade crossing collisions in the United States from 1998 to 2007, Raub (2009) shows that rail-road crossings with no controls or passive control devices (crossbucks or stop signs only) have considerably higher annual crash rates (per 10 million vehicles crossing) than rail-road crossings with gates or flashing lights (active warning devices). Further results of Anandarao (1998) show that uncontrolled rail-road crossings (without traffic control; only equipped with a level crossing sign) had higher accident rates compared to rail-road crossings equipped with a warning system and level crossing barriers (active warning devices). So rail-road crossings with level crossing sign only tend to have lower accident rates compared to rail-road crossings equipped with a warning system (active warning device). However effects were not significant in a statistical way.

Studies on accident severity show variable results. Results of Eluru et al. (2012) show that rail-road crossings with only crossbucks present, significantly increase the risk for a more severe injury severity crash, whereas rail-road crossings with barriers significantly decrease the risk for a more severe injury crash. However, crossings with stop signs (only) present also significantly decrease the risk for a more severe injury, whereas rail-road crossings with (cantilever) flashing signal lights significantly increase the risk for a more severe injury severity. This is – as described by the authors – because the sole presence of this device (without gates or stop sign) results in less safe conditions. Hu et al. 2010 – focusing on accident severity at intersections with law enforcement cameras – didn't present statistically significant results.

Table 1 presents the results of the vote-count analysis. Results show that the presence of a gate and the presence of a highway traffic signal can reduce the crash occurrence. It has to be mentioned that in some studies it was not clarified whether safety objects (such as crossbucks or signals) were used alone or combined with others. This fact might lead to differences in the results.

Table 1 Results of the vote-count analysis

	Total number of effects tested	**Result (number of effects)***				**Result (% of effects)**	
		↗	-	↘		↗	↘
Accident Frequency**	**11**	**4**	**0**	**7**		**36%**	**64%**
presence of stop sign	2	1	0	1		50%	50%
presence of gate	2	0	0	2		0%	100%
presence of flashing lights	2	1	0	1		50%	50%
presence of highway traffic signal	1	0	0	1		0%	100%
presence of bells	1	1	0	0		100%	0%
presence of crossbuck	1	0	0	1		0%	100%
no control	2	1	0	1		50%	50%
Accident Severity**	**6**	**2**	**2**	**2**		**50%**	**50%**
presence of stop sign	1	0	0	1		0%	100%
presence of gate	1	0	0	1		0%	100%
presence of flashing lights	1	1	0	0		100%	0%
presence of crossbuck	1	1	0	0		100%	0%
presence of law enforcement camera	2	0	2	0		-	-

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)
** Since exposures differ, the summarized effects for accident frequency and accident severity can't be interpreted as main results.

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

Overall 8 studies on the risk of uncontrolled rail-road crossings and 1 iRAP factsheet were selected and coded. Most of the studies (Austin and Carson 2002; Hu Lu and Tolliver 2016; Nam and Lee 2006; Yan et al. 2010) investigated accident frequency and deployed multivariable statistical models (i.e. negative binomial regression) as a method of examining the topic and controlled for other variables such as traffic volume. In these cases crash risk at rail-road crossings with passive warning devices (e.g. stop sign only) was compared with crash risk at rail-road crossings with specific active warning devices, however the approach contained a high degree of variability within cases because rail-road crossings with different types of passive warning devices were considered together within studies.

Some studies (Eluru et al. 2012; Hu et al. 2010) also focused on accident / injury severity. Other studies (Anandarao 1998; Raub 2009) only undertook a crash data analysis and calculated crash rates for different rail-road crossing types.

Most of the research (5 studies) was carried out in the United States. But also Japan (1 study), Taiwan (1 study) and South Korea (1 study).

Table 2 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 2 Description of coded studies

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Anandarao, 1998, Japan	Crash data analysis of 7894 level crossings with 1072 crashes, 1996-2000, 1987-1995	-	Rail-road crossings with traffic controls	Mean accident rates for different grade crossing types per million crossing trains
Austin, 2002, United States	Observational, negative binomial model, data of 80962 crossings with 1538 crashes, 1997-1998	Regression analysis between crossing characteristics and crash frequency	-	Focus on highway crossings
Eluru, 2012, United States	Observational, latent segmentation based ordered logit model, data of 14532 collisions between 1997 and 2006	Regression analysis between crossing characteristics and crash occurrence	-	Focus on injury severity
Hu, 2010, Taiwan	Observational, generalized logit model, data of 592 crossings, 1995-1997	Regression analysis between crossing characteristics and crash occurrence	No law enforcement camera, property damage only crashes	Focus on injury severity
iRAP, 2013, -	Factsheet, risk factors with regard to motorised vehicles, no details among method or data	Risk ratio for Cars and PTW and Cyclists	Railway Crossing - active (flashing lights/boom gates)	-

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Lu, 2016, United States	Observational, logistic model (Bernoulli),data of 5551 highway-rail grade crossingsrecords, 1996-2014	Regression between crossing characteristics and crash occurrence	Rail-road crossings with stop signs	-
Nam, 2006, South Korea	Observational, accident frequency model using zero probability process, data of 10 grade crossings	Regression between crossing characteristics and crash occurrence	Crossings with no stop sign or no control device	-
Raub, 2009, United States	Crash data analysis 31736 train-vehicle crashes, 1998-2007	-	-	Focus on annual collision rates per 10 million crossing vehicles
Yan, 2010, United States	Observational, hierarchical tree-based regression, data of 6596 crossings and 6244 train-vehicle crashes, 1980-2006	Crash rates for crossings with different characteristics	-	Traffic data: >399 vehicles/ crossing and >15 trains per day

2.3 CONCLUSION

Overall it appears that uncontrolled/passive rail-road crossings tend to have a higher crash risk compared to rail-road crossings equipped with active control devices, but this is indicated in most of the studies through a significantly lower crash risk for rail-road crossings with active control devices compared to uncontrolled/passive rail-road crossings. Only few studies actually indicate that the risk for a more severe injury crash at uncontrolled/passive rail-road crossing is higher than at rail-road crossings with active warning devices. However there is large variability within results which might be due to the fact that by their nature passive crossings are usually at low traffic volume rail-road crossings and active ones are at high traffic volume areas. If a study does not control for traffic flow it is possible that a higher reported crash frequency at active crossings is an artefact of greater traffic flow at these crossings. Furthermore, for this topic it must be emphasized, that uncontrolled/passive rail-road crossings (i.e. the signs used e.g. crossbuck only or stop sign only) differ due to national specifications which has also consequences for the effects (in part different crash risk for rail-road crossings with crossbucks or stop signs only) estimated.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

Literature search was conducted in March and April 2016. It was carried out in three databases with similar search strategies. Following databases were browsed through during the literature search: 'Scopus', 'Science Direct' and 'TRID'. Detailed search terms, as well as their linkage with logical operators and combined queries are shown in the following tables. The study scope did not exclude countries or source types like "Journal" or "Project". In some of the searches remaining studies were limited to subject areas (e.g. "Engineering"). Out of the overall 641 potentially eligible studies, after screening the abstracts of these 641 studies only from 62 studies the full-text were obtained and only 7 were coded and included in the synopsis. An additional 2 studies were identified due to other already known or during the literature search occasionally (e.g. via Google) found studies as well as studies found in the literature search for other topics and including effects for uncontrolled rail-road crossings. The reference lists of the studies were only partly checked.

Table 3 Literature search strategy, database: Scopus

search no.	search terms / operators / combined queries	hits
#1	TITLE-ABS-KEY ("safety" OR "crash" OR "risk" OR "rail" AND "crossing") AND PUBYEAR > 1989	**7,246**
#2	TITLE-ABS-KEY ("crash" OR "risk" OR "rail" AND "crossing") AND PUBYEAR > 1989	**4,904**
#3	TITLE-ABS-KEY ("crash" OR "risk" AND "rail" AND "crossing") AND PUBYEAR > 1989	**157**

Table 4 Literature search strategy, database: ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	pub-date > 1989 and "rail" AND "crossing" AND "crash"	**1,914**
#2	pub-date > 1989 and "rail" AND "crossing" AND "crash"[All Sources(Engineering,Environmental Science,Psychology,Social Sciences)].	**998**
#3	pub-date > 1989 and "rail" AND "crossing" AND "crash" AND "risk"[All Sources(Engineering,Environmental Science,Psychology,Social Sciences)].	**632**
#4	pub-date > 1989 and "rail" AND "crossing" AND "crash" AND "risk"[All Sources(Engineering)].	**384**

Table 5 Literature search strategy, database: TRID

search no.	search terms / operators / combined queries	hits
#1	"rail" AND "crossing" AND "crash"	**2,152**
#2	"rail" AND "crossing" AND "crash" AND "risk"	**364**
#3	"rail" AND "crossing" AND "crash" AND "risk"	**99**

Table 6 Results Literature Search

Database	Hits
Scopus (remaining papers after several limitations/exclusions)	157
ScienceDirect	384
TRID	99
Additional studies	1
Total number of studies to screen title/ abstract	**641**

The final 9 studies included in the synopsis indicate that the topic has not been investigated to a great extent. Studies selected to code were prioritized as follows, however all studies codable and suitable for the topic (any studies which were not crash risk specifically were excluded) were coded.

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

No meta-analyses were found.

3.1.2 Exploratory analysis of results

Table 7 presents an overview of the main outcomes of the coded studies.

Table 7 Main outcomes of coded studies for uncontrolled rail-road crossings

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
Anandarao, 1998, Japan	Traffic control	Mean accident rate / uncontrolled	-	-28,81%	Relative difference of -28,81% (higher risk) of accident rates between crossings without traffic control (only sign) compared to crossing equipped with a warning system and level crossing barrier
	Traffic control	Mean accident rate / uncontrolled	-	39,20%	Relative difference of 39,2% (lower risk) of accident rates between crossings without traffic control (only sign) compared to crossing equipped only with a warning system
Austin, 2002, United States	Traffic control	Crash count / presence of a stop sign	↗	r= 19,615, 95% CI	Significant negative effect of presence of stop sign on accident frequency.
	Traffic control	Crash count / presence of a gate	↘	r= -2,974, 95% CI	Significant positive effect of presence of a gate on accident frequency.
	Traffic control	Crash count / presence of flashing lights	↗	r= 1,075, 95% CI	Significant negative effect of presence of flashing lights on accident frequency.

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Traffic control	Crash count / presence of a highway traffic signal	↘	r= -114,447, 95% CI	Significant positive effect of presence of highway traffic signal on accident frequency.
	Traffic control	Crash count / presence of bells	↗	r= 0,649, 95% CI	Significant negative effect of presence of presence of bells on accident frequency.
Eluru, 2012, United States	Traffic control	Crash count / presence of cantilever flashing light signals, with low risk of injury severity	↗	r= -0,1898	Significant negative effect of cantilever flashing light signals on occurrence of crashes with low risk of injury severity
	Traffic control	Crash count / presence of stop sign, with low risk of injury severity	↘	r= 0,1959	Significant positive effect of presence of stop sign on occurrence of crashes with low risk of injury severity
	Traffic control	Crash count / presence of crossbucks, with low risk of injury severity	↗	r= -0,3291	Significant negative effect of presence of crossbuck on occurrence of crashes with low risk of injury severity
	Traffic control	Crash count / presence of gates, with low risk of injury severity	↘	r= 1,3012	Significant positive effect presence of gates on occurrence of crashes with low risk of injury severity
	Traffic control	Crash count / presence of cantilever flashing light signals, no injury	-	e=-2,9	Positive effect of cantilever flashing light signals on no injury highway-railway crash occurrence
	Traffic control	Crash count / presence of stop sign, no injury	-	e=2,8	Negative effect of stop sign on no injury highway-railway crash occurrence
	Traffic control	Crash count / presence of crossbucks, no injury	-	e=-4,6	Positive effect of crossbucks on no injury highway-railway crash occurrence
	Traffic control	Crash count / presence of gates, no injury	-	e=16,3	Negative effect of gates on no injury highway-railway crash occurrence
	Traffic control	Crash count / presence of cantilever flashing light signals, severe injury	-	e=4,6	Negative effect of cantilever flashing light signals on severe injury highway-railway crash occurrence
	Traffic control	Crash count / presence of stop sign, severe injury	-	e=-4,4	Positive effect of stop sign on severe injury highway-railway crash occurrence
	Traffic control	Crash count / presence of crossbucks, severe injury	-	e=7,4	Negative effect of crossbucks on severe injury highway-railway crash occurrence
	Traffic control	Crash count / presence of gates, severe injury	-	e=-24,9	Positive effect of gates on severe injury highway-railway crash occurrence
	Traffic control	Crash count / presence of cantilever flashing light signals, fatal	-	e=4,7	Negative effect of cantilever flashing light signals on fatal highway-railway crash occurrence

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Traffic control	Crash count / presence of stop sign, fatal	-	e=-4,5	Positive effect of stop sign on fatal highway-railway crash occurrence
	Traffic control	Crash count / presence of crossbucks, fatal	-	e=7,6	Negative effect of crossbucks on fatal highway-railway crash occurrence
	Traffic control	Crash count / presence of gates, fatal	-	e=-29,6	Positive effect of gates on fatal highway-railway crash occurrence
Hu, 2010, Taiwan	Presence of law enforcement camera	Crash severity / severe injury	-	r= -1,699, p=0,0627, OR=0,183	Non-significant positive effect of law enforcement camera on risk of severe injury
	Presence of law enforcement camera	Crash severity / minor injury	-	r= -1,392, p=0,0627, OR=0,249	Non-significant positive effect of law enforcement camera on risk of minor injury
iRAP, 2013, -	No traffic control	Crash count / Car & PTW	-	RR=2	Risk car or PTW crash at uncontrolled rail-road crossings is twice that high than at active railway crossings (flashing lights/boom gates)
	No traffic control	Crash count / Cyclists	-	RR=3	Risk car or cylist crash at uncontrolled rail-road crossings is three times higher that high than at active railway crossings (flashing lights/boom gates)
Lu, 2016, United States	Traffic control	Crash count / Crossbuck	↘	r=-0,797, 99% CI	Significant positive association between crossbuck and accident likelihood
	Traffic control	Crash count / Gate	↘	r=-0,1698, 99% CI	Significant positive association between gate and accident likelihood
	Traffic control	Crash count / No control	↘	r=-3,0864, 99% CI	Significant positive association between stop sign accident likelihood
	Traffic control	Crash count / Flashes	↘	r=-1,9378, 99% CI	Significant positive association between flashes and accident likelihood
Nam, 2006, South Korea	Traffic control	Crash count / Stop sign	↘	r=-0,495, e=-0,667	Significant positive effect of stop sign at crossing on accident likelihood compared to no stop sign
	Traffic control	Crash count / Control device	↘	r=-0,818, e=-0,103	Significant positive effect of control device at crossing on accident likelihood compared to no control device
Raub, 2009,	Traffic control	Crash count / crossbucks	-	28,8	Crossings with crossbuck have annual crash rate(10 million vehicles crossing) of 28,8

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
United States	Traffic control	Crash count / stop signs	-	37,4	Crossings with stop sign have annual crash rate(10 million vehicles crossing) of 37,4
	Traffic control	Crash count / flashing lights	-	5,1	Crossings with flashing lights have annual crash rate(10 million vehicles crossing) of 5,1
	Traffic control	Crash count / gates	-	4,1	Crossings with gates have annual crash rate (10 million vehicles crossing) of 4,1
Yan, 2010, United States	Traffic control	Crash count / Absence of railroad advance warning signs - Test group	-	0,078	Crashes per year and crossing
	Traffic control	Crash count / Presence of railroad advance warning signs - Test group	-	0,123	Crashes per year and crossing

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

3.2 FULL LIST OF STUDIES

3.2.1 List of studies

A detailed list of studies coded is presented below:

Anandarao, S. / Martland, C. D. (1998): Level crossing safety on East Japan Railway Company: Application of probalistic risk assessment techniques. In: Transportation; Aug1998, Vol. 25 Issue 3, pp. 265-286.

Austin, R.D. / Carson, J.L. (2002): An alternative accident prediction model for highway-rail interfaces. In: Accident Analysis and Prevention Vol. 34, pp. 31-42.

Eluru, N. / Bagheri, M. / Miranda-Moreno, L.F. / Fu, L. (2012): A latent class modeling approach for identifying vehicle driver injury severity factors at highway-railway crossings. In: Accident Analysis and Prevention 47, pp. 119-127.

Hu, S. / Li, C. / Lee, C. (2010): Investigation of key factors for accident severity at railroad grade crossings by using a logit model. Safety Science 48, pp. 186-194.

iRAP (2013). iRAP Road Attribute Risk Factors. Intersection Type. International Road Assessment Programme (iRAP).

Lu, P. / Tolliver, D. (2016): Accident prediction model for public highway-rail grade crossings. In: Accident Analysis and Prevention 90, pp. 73-81.

Nam D. / Lee J. (2006): Accident Frequency Model Using Zero Probability Process. In: Transportation Research Record Vol. 1973, pp. 142-148.

Raub, R.A. (2009): Examination of highway-rail grade crossing collisions nationally from 1998 to 2007. In: Transportation Research Record: Journal of the Transportation Research Board No. 2122, pp. 63-71.

Yan, X. / Richards, S. / Su, X. (2010): Using hierarchical tree-based regression model to predict train-vehicle crashes at passive highway-rail grade crossings. In: Accident Analysis and Prevention 42, pp. 64-74.

3.2.2 References on further background information

Wullems, C. / Hughes, P. / Nikandros, G. (2013): Modelling risk at low exposure railway level crossings: supporting an argument for low-cost level crossing warning devices with lower levels of safety integrity. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 227(5), pp. 560-569.

Synopsis 36: Poor junction readability-Uncontrolled junctions

1 Summary

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September 2016

COLOUR CODE: YELLOW

Explanation: Uncontrolled junctions are probably risky as crashescrashes tend to be more severe. However, some studies indicate that the total number of crashes at uncontrolled junctions are fewer than at controlled junctions. This result could be attributed to exposure as traffic is lower and fewer pedestrians cross at uncontrolled junctions. A number of studies indicate that most mid-block crashes occur near uncontrolled junctions. Overall, it can be thus argued that fewer but more severe crashes occur at uncontrolled junctions.

KEYWORDS

Uncontrolled; junctions; intersections; vulnerable road users; crashes; frequency; severity

1.1 ABSTRACT

Overall, the effect of uncontrolled junctions on road safety was not entirely clear however, it can be considered risky. Some counterintuitive findings also exist in literature. More specifically, literature suggests that fewer crashes occur at uncontrolled junctions. This could be attributed to limited exposure at these areas and to the fact that a portion of crashes with pedestrians that might have occurred at uncontrolled junctions actually occur at mid-block locations, because pedestrians choose to cross before reaching a junction. On the other hand, it was found that crashes at uncontrolled junctions tend to be more severe, but not always when crash types are examined separately. The vote count analysis that was carried out on the basis of 8 coded studies confirms this tendency. It is noted that most of literature explores the effect of various traffic control measures of junctions on safety rather than the risk of uncontrolled junctions.

1.2 BACKGROUND

1.2.1 Definitions of uncontrolled junctions

Studies refer to this risk factor as intersections or junctions with "no control" or simply "uncontrolled" and define it as discrete variable (present vs absent).

1.2.2 How does uncontrolled junctions affect road safety?

Junctions are one of the most dangerous locations of a roadway network, since they are not only a convergence point for vehicles and pedestrians but also impose significant responsibility on successful gap judgements. Furthermore, intersections are a source of traffic congestion, and have a prevalence of severe side-impact crashes. Intuitively controlling a junction would separate the traffic and therefore decrease crashes. At uncontrolled junctions road users have to take important decisions regarding accepted gaps. Moreover, human errors could easily lead to crashes.

1.2.3 Which safety outcomes are affected by uncontrolled junctions?

In international literature, the effect of uncontrolled junctions on road safety has been mainly investigated on the basis of crash frequency (number of crashes occurred). Less frequently, uncontrolled junction was found to affect crash severity (fatal vs non-fatal injury etc.). Other outcome indicators such as crash risk (probability of crash occurrence) or crash type (car vs car or car vs motorcycle) have also been investigated.

1.2.4 How is the effect of uncontrolled junctions studied?

Much literature has investigated crashes at junctions. Most studies prefer to focus on the effect of controlled junctions (police, stop, signalized) rather than uncontrolled junctions. Nevertheless, there is a number of studies examining the risk of an uncontrolled junction by considering its effect on the number of crashes, risk of crash occurrence or severity of crashes. Multivariable statistical models constitute the primary way of analysing the aforementioned effects. A focus on vulnerable road users such as motorcyclists, cyclists or pedestrians is also observed.

1.3 OVERVIEW OF RESULTS

The examination of relevant studies suggests a couple of counterintuitive findings as suggested by some authors of the coded studies. More specifically, a number of studies (Lee and Abdel-Aty, 2005; Poch, 1996) found that uncontrolled junctions have lower crash frequency and crash risk (Bennet and Yiannakoulias, 2015), suggesting that most of crashes tend to happen at controlled junctions. One possible explanation of this rather counterintuitive finding, is that the majority of mid-block crashes may occur near uncontrolled junctions (Ha and Thrill, 2011; Zandt and Zegeer, 2006). Thus, pedestrians prefer to cross in midblock than in uncontrolled junction. Consequently, the uncontrolled junction has a hidden relationship with crashes and causes "crash mitigation", because crashes that would happen in uncontrolled junctions happen now a few meters away. On the other hand, it is suggested that crashes at uncontrolled junctions are high likely to result in more severe outcomes as suggested by Pai and Saleh (2008), Sarkar et al. (2011) and Wang and Stamatiadis (2011). However, a recent study by Wu et al. (2016) which examines injury severity of drivers in single-vehicle crashes on rural and urban roadways, suggests that traffic control[1] does not play a role in crash severity. Most of coded studies consider junctions in US and Canada, while some studies concern other countries outside Europe, such as New Zealand (Walton et al., 2013), Japan (Hiramatsu et al., 2003) and Bangladesh (Sarkar et al., 2011). Significant effort was made to study various road user categories like pedestrians and cyclists. The heterogeneous study designs makes it difficult to claim transferability of results, however, it could be concluded that fewer but more severe crashes occur at uncontrolled junctions compared with controlled junctions.

1.4 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and methodologically sound. Simpler approaches (e.g. absolute proportions) also exist. The main potential bias indicated in some of the studies, is the fact the applied statistical methods and model specifications applied in these studies (fixed effects negative binomial models and ordered probit models) do not account for unobserved heterogeneity[2] that is possibly present because, they assume the effect of the explanatory variable on frequency (or severity) of crashes is constrained to be the same for all observations (e.g. cyclists). Consequently, the resulting parameter estimates may be biased. Overall, the effect of uncontrolled junctions on road safety could be considered to be adequately explored. Nevertheless, most of literature examines the effect of traffic control rather than the effect of no control, thus providing an indirect relationship. In that context, the effect of uncontrolled junctions on safety and especially crash severity needs further examination. Moreover, the lack of European studies is another issue that needs to be tackled.

[1] It has to be noted though that in that study, traffic control does not concern only junctions.
[2] For more detail, the reader is encouraged to refer to Karlaftis and Tarko (1998) and Washington et al. (2010).

2 Scientific overview

2.1 LITERATURE REVIEW

Junction are considered one of the most dangerous locations of a roadway network, since they are not only a convergence point for vehicles and pedestrians but also impose significant responsibility on successful gap judgements. Furthermore, junctions are a source of traffic congestion and have a prevalence of severe side-impact crashes. At uncontrolled junctions in particular, road users have to take important decisions regarding accepted gaps. Thus, human errors are more likely to occur.

Much research has been carried out on the topic of safety at junctions. Early research argues that signalization could be very influential in intersection safety (Solomon, 1959; Cribbins et al., 1967; Cribbins et al., 1970; Van Maren 1980). It is observed that most studies prefer to focus on the effect of traffic control at junctions (police, stop, signalized) rather than presence of no traffic control (Chen et al., 2012; Haleem et al., 2010; Kamruzzaman et al., 2013; Kim et al., 2007; Pei and Fu, 2014).

Usually, the presence of no control at junctions or the so called "uncontrolled junction" is examined as a discrete variable (e.g. no-control vs traffic control). The influence of uncontrolled junctions on road safety is investigated by different approaches such as estimating the number of crashes (crash frequency), crash severity and more rarely crash risk and crash type.

It is observed that that the main focus of international literature has been on the effect of various traffic control types and measures on road safety rather than the presence of no control at junctions. Such measures are not considered here. Additional research on the risk of uncontrolled junctions is needed, as the issue of counterintuitive findings in literature has been recognized (Bennet and Yiannakoulias, 2015; Lee and Abdel-Aty, 2005). Consequently, this issue needs to be addressed on the basis of more research with various designs, methods and sampling frames especially in European countries which are seriously underrepresented in literature.

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

8 studies of sufficient quality were coded. There is great variation among the outcome indicator of interest in each study. A few studies focus on crash numbers (Poch, 1996; Lee and Abdel-Aty, 2005; Hiramatsu et al., 2003) and on crash severity (Sarkar et al., 2011; Wang and Stamatiadis, 2011). Only one study focused on crash risk-probability of crash occurrence (Bennet and Yiannakoulias (2015) and another one focused on collision type (Walton et al., 2013).

Most of coded studies consider junctions in USA and Canada, while some studies concern other countries outside Europe, such as New Zealand (Walton et al., 2013), Japan (Hiramatsu et al., 2003) and Bangladesh (Sarkar et al., 2011). It is remarkable that only 1 European study was identified through the literature review.

Significant effort was made to study various road user categories like pedestrians and cyclists. The majority of studies considered vulnerable road users. More specifically, Bennet and Yiannakoulias (2015) examined child pedestrian-related crashes with motor-vehicles at junctions of Hamilton, Ontario in Canada. Lee and Abdel-Aty (2005) considered vehicle-pedestrian crashes in Florida State, US, while Wang and Stamatiadis (2011) explored crashes involving bicycles at unsignalized junctions in Kentucky, US. Walton et al. (2013) attempted to estimate the effect of uncontrolled junctions on crash type and especially on the distinction between cars vs cars collisions and cars vs motorcycles.

In order to examine the underlying relationships between uncontrolled junctions and outcome indicators, studies deployed appropriate multivariable statistical models. However, not all studies used models but relied on simpler methods instead (Hiramatsu et al., 2003). Most studies deployed straightforward statistical methods (e.g. negative binomial models, ordered probit models).

In general, the coded studies are of sufficient quality and methodologically sound. One potential bias indicated in some of the studies, is that they do not account for unobserved heterogeneity that is possibly present. This is because the model specifications (fixed effects negative binomial models and ordered probit models) assume that the effect of the explanatory variable on road safety is constrained to be the same for all observations (freeway diverge areas). Consequently, the resulting parameter estimates may be biased.

Studies suggest that a couple of counterintuitive findings exist as stated by some authors. More specifically, some authors found that uncontrolled junctions are negatively associated with crash frequency and crash risk (Bennet and Yiannakoulias, 2015), implying that the majority of crashes tend to occur at controlled junctions. For example, Lee and Abdel-Aty (2005) state that more investigation is needed to explain that more crashes occurred at the junctions with traffic control (other than traffic signal) than the junctions without traffic control. Similarly, Bennet and Yiannakoulias (2015) found that more child pedestrian crashes seem to occur in intersections without traffic control. Authors report this result as counterintuitive. One possible explanation of this result is that the majority of mid-block collisions may occur at locations with no signals or crosswalk present whilst in contrast, most intersection collisions occur at junctions with signals or stop signs present (Ha and Thrill, 2011; Zandt and Zegeer, 2006).

On the other hand, it is suggested that crashes at uncontrolled junctions are high likely to result in more severe outcomes as suggested by Sarkar et al. (2011) and Wang and Stamatiadis (2011). However, a recent study by Wu et al. (2016) which examines injury severity of drivers in single-vehicle crashes on rural and urban roadways, suggests that traffic control does not play a role in crash severity. On the other hand, Pai and Saleh (2008) examined motorcyclist injury severity at T-junctions. When total crashes are considered, severity of motorcycle crashes are higher. However, the results vary according to the crash type (i.e. when severity is examined separately for each crash type).

The heterogeneous study designs makes it difficult to claim transferability of results, however, it could be concluded that fewer but more severe crashes occur at uncontrolled junctions. Overall, it can be observed that more research is needed to confirm the hypothesis that fewer but more severe crashes occur at uncontrolled junctions. In that context, more research on various categories of road users should be carried out especially in European countries.

Table 1 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 1 Description of coded studies.

Author(s), Year	Sample and study design	Method of analysis	Unit of analysis	Outcome indicator	Main result
Bennet and Yiannakoulias, 2015	92 motor-vehicle-child pedestrian collisions at junctions in the city of Hamilton, Ontario in Canada between 2002 and 2011	Matched case–control study design and apply it to intersection and conditional logistic regression	Presence of uncontrolled junction	Crash risk (probability of crash occurrence)	More child pedestrian crashes seem to occur in junctions with traffic control. Authors report this result as counterintuitive
Lee and Abdel-Aty, 2005	7,000 vehicle–pedestrian crashes at junctions in Florida over 4 years, 1999–2002	Log-linear models	Presence of uncontrolled junction	Number of vehicle-pedestrian crashes	The frequency of crashes at driver's fault was higher at junctions with traffic control than the intersections without traffic control
Hiramatsu et al., 2003	Crashes at junctions in Japan for the year 2000	Absolute proportion	Presence of uncontrolled junction	Daytime, night-time and total crashes	A large portion of total crashes occurred in daytime at uncontrolled intersections where the primary party is required to stop
Pai and Saleh, 2008	100,162 motorcycle crashes T-junctions in UK for 1991-2004.	Ordered logit model	Presence of uncontrolled junction	Crash severity	Overall, motorcycle crashes tend to be more severe at uncontrolled T-junctions. However, results vary when crash types are examined separately.
Poch, 1996	Crashes at junctions in City of Bellvue, Washington State for the year 2000	Negative binomial model	Presence of uncontrolled junction	Number of crashes separately (all types, angle crashes, rear-end crashes and approach turn crashes)	Less total crashes and angle crashes occur at uncontrolled junctions
Sarkar et al., 2011	4,976 crashes in junctions of junctions in Bangladesh from 1998 to 2006	Binary logistic regression model	Presence of uncontrolled junction	Crash severity**	More severe crashes are more probable to happen at uncontrolled junctions
Walton et al., 2013	305 car versus car and car versus Motorcycle crashes in New Zealand from 2004 to 2009	Case-control study and odds ratio	Presence of uncontrolled junction	Collisions of car vs car or motorcycle (CVC or CVM)	Crashes with cars and motorcycles are more likely to occur at uncontrolled junctions
Wang and Stamatiadis, 2011	1,242 bicycle related crashes at unsignalized junctions in Kentucky between 2000 and 2009	Ordered probit model	Presence of uncontrolled junction	Bicyclist crash severity***	More severe bicyclist crashes tend to happen at uncontrolled junctions

*1: no injury, 2:slight injury, 3:Killed or severely injured (KSI)
** 1: non-fatal, 2: fatal
*** 1: None/slight injured, 2:non-incapacitating, 3: incapacitating, 4: fatal

2.3 ANALYSIS METHODS AND RESULTS

2.3.1 Introduction

The effects of uncontrolled junctions identified can be summarized as follows:

- 1 study with significant decrease on numbers of total and angle crashes
- 1 study with significant decrease on numbers drivers' fault crashes
- 1 study suggesting that a large portion of crashes (absolute proportion) occurs at uncontrolled junctions
- 1 study with significant decrease in motor-vehicle-child pedestrian crashes at uncontrolled junctions
- 1 study with significant increase in total crash severity at uncontrolled junctions
- 1 study with significant increase in bicyclist crash severity at uncontrolled junctions
- 1 study with significant increase in motorcycle crash severity at T-uncontrolled junctions but with inconsistent findings when crash types are examined separately
- 1 study with significant increase in car vs motorcycle crash occurrence at uncontrolled junctions

After the results were reviewed together to decide if meta-analysis is possible, the following points were observed:

a) There is an adequate number of studies, however;
b) Those studies have not used the same model for analysis but radically different ones.
c) There are different indicators, and even when they coincide they are not measured in the same way.
d) The sampling frames were quite different.
e) Some studies indicate that fewer crashes tend to occur at junctions without any traffic control.
f) Crashes at uncontrolled junctions are more likely to more severe.

2.3.2 Vote count analysis

Due to presence of strong heterogeneity in study designs, samples and methods of analysis, it was not feasible to carry out a meta-analysis. Therefore, it was not possible to produce an overall estimate of uncontrolled junction and alternative approaches were sought such as the vote-count analysis.

Table 2: Vote-count analysis results for uncontrolled junction

Outcome definition*	Tested in number of studies	Result (number of studies)			Result (% of studies)			Result (number of effects)			Result (% of effects)		
		↑	-	↓	↑	-	↓	↑	-	↓	↑	-	↓
Crash frequency	2	-	-	2	-	-	100%	1	2	5	12.50%	25%	62.50%
Crash risk	1	-	-	1	-	-	100%	-	-	3	-	-	100%
Crash or injury severity	4	3	1	-	75.00%	25.00%	-	7	5	1	53.85%	38.46%	7.69%
Crash type (car vs var and car vs motorcycle)	1	1	-	-	100%	-	-	1	-	-	100%	-	-

* Hiramatsu et al. (2003) was not included in the analysis because the authors reported only absolute proportions.

On the basis of both study and effect numbers, it can be argued that the risk factor of uncontrolled junction, with all its variations, has a mixed effect on road safety. However, it can be concluded that fewer total crashes are more likely to occur at uncontrolled junctions but would likely be more severe in general. Furthermore, a number of authors (Ha and Thrill, 2011; Zandt and Zegeer, 2006) indicate that the majority of mid-block crashes may occur at locations with no signals or crosswalk present whilst in contrast, most junction crashes occur at junctions with signals or stop signs present, making them hard to compare. Therefore it was decided to mark this risk factor as "yellow" although there are some mixed findings about the influence of this risk factor on safety.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

The search strategy aimed at identifying the best quality and recent studies to estimate the effect of this risk factor. In general, only recent journal studies (after 1990) in the field of Engineering were initially considered from the Scopus database. Out of 127 potentially eligible studies, 25 were found to be mostly relevant to the topic. However, after a full-text screening 8 quality studies were coded and 1 was problematic (Wu et al., 2016) but considered useful and informative and decided to be included in the synopsis.

Table 3 Literature search strategy.

search no.	search terms / operators / combined queries	hits
#1	(„uncontrolled junction")	99
#2	(„uncontrolled junction" OR "uncontrolled intersection")	237
#3	(„casualties" OR „fatalities" OR „traffic safety" OR „crash" OR „crash risk" OR „severity" OR „frequency" OR „collision" OR „incident" OR „accident")	22,319
#4	#1 AND #3	35
#5	#2 AND #3	122
#6	(„uncontrolled junction" OR "uncontrolled intersection" OR „intersection" OR „junction")	288
#7	(„junction" OR "intersection")	95,197
#8	#7 AND #3	3,539
#9	#7 AND #3 (search field: TITLE-ABS-KEY)	938
#10	**#6 AND #3**	**127**

The final 8 studies coded and indicate that the topic has not been relatively investigated. The prioritizing criteria were the following:

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

No "grey" literature was examined and no meta-analyses were found. Among the final eligible studies, there was a study identified as very relevant (Wu et al., 2016) and although it was problematic in coding it was decided to be included in the synopsis.

3.2 SUMMARY OF RESULTS

The results of the coded studies are summarized in Table 4.

Number	Author(s); Year;Country	Outcome indicator	Quantitative estimate	Effect on road safety
1	Bennet and Yiannakoulias; 2015; Canada	Crash risk[probability of crash occurrence]	Child pedestrian activity using shortest distance: OR= 0.07, CI[95%]=[0.02,0.31]	↓
			Child population: OR= 0.08, CI[95%]=[0.02,0.32]	↓
			Child pedestrian activity using preferred route: OR= 0.08, CI[95%]=[0.02,0.38]	↓
2	Lee and Abdel-Aty; 2005; USA	Crash frequency [number of vehicle-pedestrian crashes]	All areas, driver's fault: beta coefficient=-0.8357, st.error=0.2103	↓
			Urban areas, driver's fault: beta coefficient=-0.2687, st.error=0.2648	↓
			All areas, pedestrian's fault: beta coefficient=0.015, st.error=0.1308	↑
			Rural areas, pedestrian's fault: beta coefficient=-0.02293, st.error=0.1733	↓
3	Hiramatsu et al., 2003; Japan	Absolute proportion [number of crashes due to uncontrolled junction]	Daytime: proportion=20.69%	-
			Nightiime: proportion=4.09%	-
			All: proportion=24.78%	-
4	Poch; 1996; USA	Crash frequency [number of crashes]	Total crashes: beta coefficient=-0.753, t-test=4.4	↓
			Angle crashes: beta coefficient=-21.36, t-test=4.75	↓
5	Sarkar et al.; 2011; Bangladesh	Crash severity[fatal, non-fatal]	OR=2.713, CI[95%]=[1.513,4.864]	↑
6	Walton et al. ; 2013; New Zealand	Collisions of cars with motorcycles vs collision of cars with cars	OR=1.96, CI[95%]=[1,3.86]	↑
7	Wang and Stamatiadis; 2011; USA	Bicyclist injury severity [none/slight injured, non-incapacitating, incapacitating, fatal]	Beta coefficient (same for all severity levels)=0.561, p-value=0.039	↑
8	Wu et al.; 2016; USA****	Crash severity [no apparent injury, complaint of injury, visible injury, incapacitating injury, killed	Urban single-vehicle crashes, nested logit model: not retained in the final model	-

			Urban single-vehicle crashes, mixed logit model: not retained in the final model	-
9	Pai and Saleh; 2008; UK	Motorcyclist injury severity [no injury, injury, KSI]	Total crashes: beta coefficient=0.154, p-value=<0.0001	↑
			Head-on crashes: beta coefficient=0.56, p-value=0.031	↑
			Sideswipe crashes: beta coefficient=0.369, p-value=<0.0001	↑
			Rear-end approach A crashes: beta coefficient=0.201, p-value=0.103	↑
			Rear-end approach B crashes: beta coefficient=0.226, p-value=0.179	-
			Approach turn A crashes: beta coefficient=-0.504, p-value=0.055	↓
			Approach turn B crashes: beta coefficient=0.124, p-value=0.122	-
			Angle A crashes: beta coefficient=-0.099, p-value=0.298	-
			Angle B crashes: beta coefficient=0.425, p-value=0.01	↑

**** Study of Wu et al., (2016) was problematic and was not coded.

3.3 LIST OF STUDIES

3.3.1 List of coded studies

A detailed list of studies coded is provided below:

1) Bennet S., Yiannakoulias N. (2015). Motor-vehicle collisions involving child pedestrians at intersection and mid-block locations. Accident Analysis and Prevention 78, 94–103. doi: http://dx.doi.org/10.1016/j.aap.2015.03.0012.
2) Hiramatsu, M., Obarab, H., Umezaki, K. (2003). Broadside collision scenarios for different types of pre-crash driving patterns. JSAE Review, 24, 327-334. doi: http://dx.doi.org/10.1016/S0389-4304(03)00033-X.
3) Lee C., Abdel-Aty M. (2005). Comprehensive analysis of vehicle–pedestrian crashes at intersections in Florida. Accident Analysis and Prevention 37, 775–786. doi: 10.1016/j.aap.2005.03.019.
4) Pai C.-W., Saleh, W. (2008). Modelling motorcyclist injury severity by various crash types at T-junctions in the UK. Safety Science 46, 1234-1247. doi: 10.1016/j.ssci.2007.07.005.
5) Poch, M., Mannering, F. (1996). Negative binomial analysis of intersection-accident frequencies. Journal of Transportation Engineering. 122(2), March/April, 1996. ISSN 0733-

947X19610002-0105-0113-Paper No. 10216. doi: http://dx.doi.org/10.1061/(ASCE)0733-947X(1996)122:2(105).

6) Sarkar S., Tay R., Hunt J.D. (2011). Logistic Regression Model of the Fatality Risk of Vehicle-Pedestrian Crashes on National Highways in Bangladesh. 2011 TRB Annual Meeting, Washington D.C., USA.

7) Walton, D., Buchanan, J., Murray, S.J. (2013). Exploring factors distinguishing car-versus-car from car-versus-motorcycle in intersection crashes. Transportation Research Part F: Psychology and Behaviour, 17, 145-153. doi: 10.1016/j.trf.2012.11.001.

8) Wang C., Stamatiadis N. (2011). Bicyclist Injury Severity in Bicycle-Motor Vehicle Crashes at Unsignalized Intersections in Kentucky. TRB 2011 Annual Meeting, Washington D.C., USA.

Other references

1) Chen H., Cao L., Logan D.B. (2012). Analysis of Risk Factors Affecting the Severity of Intersection Crashes by Logistic Regression. Traffic Injury Prevention 13(3), 300-307. doi: 10.1080/15389588.2011.653841

2) Cribbins P., Arey J., Donaldson J. (1967). Effects of selected roadway and operational characteristics on accidents on multilane highways. Highway Research Record 188, Highway Research Board, Washington, D.C., 1967, 8-25.

3) Cribbins P., Walton C. (1970). Traffic signals and overhead flashers at rural intersections: Their effectiveness in reducing accidents. Highway Research Record 325, Highway Research Board, Washington, D.C., 1970, 1-14.

4) Ha H.H., Thrill J.C. (2011). Analysis of traffic hazard intensity: a spatial epidemiology case study of urban pedestrians. Computers Environment and Urban Systems 35 (3), 230–240. doi: http://dx.doi.org/10.1016/j.compenvurbsys.2010.12.004.

5) Haleem K., Abdel-Aty M., Mackie K. (2010). Using a reliability process to reduce uncertainty in predicting crashes at unsignalized intersections. Accident Analysis and Prevention 42, 654-666. doi: 10.1016/j.aap.2009.10.012.

6) Kamruzzaman, M., Haque, M.M., Ahmed, B., Yasmin, T. (2013). Analysis of traffic injury severity in a mega city of a developing country. 4th Road Safety International Conference, Sydney, Australia. doi: http://discovery.ucl.ac.uk/1418957/.

7) Karlaftis M.G., Tarko, A. (1998). Heterogeneity considerations in accident modeling. Accident Analysis and Prevention 30 (4), 425–433.

8) Kim D.-G., Lee Y., Washington S., Choi K. (2007). Modeling crash outcome probabilities at rural intersections: Application of hierarchical binomial logistic models. Accident Analysis and Prevention 39, 125–134. doi: 10.1016/j.aap.2006.06.011.

9) Pei Y., Fu C. (2014). Investigating crash injury severity at unsignalized intersections in Heilongjiang Province, China. Journal of Traffic and Transportation Engineering (English Edition) 1(4), 272-279.

10) Sandt L., Zegeer C.V. (2006). Characteristics related to midblock pedestrian–vehicle crashes and potential treatments. Transportation Research Record 1982, 113–121.

11) Solomon D. (1959). Traffic signals and accidents in Michigan. Public Roads 30(10), 234-237.

12) Van Maren P. (1980). Correlation of design and control characteristics with accidents at rural multilane highway intersections. Purdue University and Indiana State Highway Commission, July 1980.

13) Washington S.P., Karlaftis M.G., Mannering F.L. (2010). Statistical and econometric methods for transportation data analysis. Chapman & Hall/CRC.

14) Wu Q., Zhang G., Zhu X., Liu X.C., Tarefder R. (2016). Analysis of driver injury severity in single-vehicle crashes on rural and urban roadways. Accident Analysis and Prevention 94, 35–45. http://dx.doi.org/10.1016/j.aap.2016.03.026.

Synopsis 37: poor junction readability - absence of road markings and crosswalks

1 Summary

Soteropoulos, A. & Stadlbauer, S., September 2016

1.1 COLOUR CODE: YELLOW

From studies on the effects of the absence of road markings and crosswalks at intersections it appears that the lack of these features (e.g. stop lines) may lead to more severe crashes. However for studies considering crash risk, variable effects for the absence of road markings and crosswalks can be observed.

1.2 KEYWORDS

Junction, markings, crosswalk, intersection

1.3 ABSTRACT

Regarding the effects of absence of road markings and crosswalks on road safety, it can be observed that studies on accident frequency show differing results: some studies indicate a higher crash risk at intersections where road markings or crosswalks are absent, however other studies also show contrary results. Studies on accident severity mainly show a (significant) higher injury severity at intersections without markings or crosswalks. Thus intersections without road markings and crosswalks tend to lead to more severe crashes in urban as well as in rural settings.

1.4 BACKGROUND

1.4.1 What is absence of road markings and crosswalks?

Road markings at intersections help road users to get information to identify or navigate through the intersection. This is especially the case at intersections where traffic controls or traffic signs are scarce or absent, e.g. at unsignalized intersections (UIIG, 2015). Crosswalk markings are intended to guide pedestrians in a safe path across the road in a way that can be seen by drivers, and to alert motorists that pedestrians may be encountered (Koepsell et al. 2002). However, road markings and crosswalk don't exist at all intersections.

1.4.2 How does the absence of road markings and crosswalks affect road safety?

As road markings provide information for identifying and navigating intersections, with the absence of road markings dangerous conditions are likely to occur (Department of Traffic 2006). In addition especially when crossing the major road with no dedicated pedestrian at unsignalized intersections, an increased probability of jaywalking can be observed (Haleem et al. 2015).

1.4.3 Which safety outcomes are affected by the absence of road markings and crosswalks?

In the international literature, the effect of the absence of road markings and crosswalks on road safety, accident frequency (number of crashes occurred) and accident severity (severity of injuries of occupants given that an accident has occurred) has been measured. Moreover some studies focused on the behaviour of drivers or pedestrians, providing an indication of road safety effects.

1.4.4 How is the effect of the absence of road markings and crosswalks studied?

International literature indicated that the effect of the absence of road markings and crosswalks at intersections is usually examined by applying multivariable linear statistical models. In accident frequency models, the relationship between the absence (or existence) of road markings and crosswalks with the number of crashes, is most commonly investigated using negative binomial models. In accident severity models, the studies identified applied binary probit and mixed/multivariate binomial logit models. Studies focusing on the behaviour of drivers and pedestrians deployed logistic regression models or used a case-control design. Studies mostly focused on motor vehicle and pedestrian crashes. Most research has been done in the United States but also a European study (from the Netherlands) was found.

1.5 OVERVIEW RESULTS

Regarding the effects of the absence of road markings and crosswalks on road safety, it appears that intersections with absent road markings and crosswalks tend to lead to more severe crashes (i.e. an increase to injury severity), whereas variation between study results mean that the impact on crash risk is unclear. Studies on accident severity though mainly show a (significant) higher injury severity at intersections without markings or crosswalks or a (significant) lower injury severity at intersections with markings or crosswalks respectively.

Some studies on accident frequency indicate a higher crash risk at intersections where road markings or crosswalks were absent or a lower crash risk at intersections with present markings or crosswalks respectively (e.g. because crosswalks provide a protected crossing area for pedestrians). However other studies show increased crash risk with the presence of road markings and crosswalks e.g. because crosswalks probably give pedestrians a false sense of security. Also studies focusing on the behaviour of drivers or pedestrians mostly showed negative effects for the absence of road markings and crosswalks on road safety.

1.6 NOTES ON ANALYSIS METHODS

In general, the coded studies are of sufficient quality and are methodologically sound. However in one study it is mentioned that it was attempted to measure and control for several relevant factors, but confounding by other unmeasured site characteristics cannot be ruled out entirely.

Overall, the topic has not been very deeply studied (number of relevant studies is 10). Furthermore it must be emphasised that especially for road markings a great variety of markings (e.g. stop lines or markings for bicycles etc.) exist. Moreover research was mostly carried out in the United States (only one European study was found) which has implications especially for crosswalks as their design etc. is linked to national specifications. The variability in findings between studies for the effect of an absence of crosswalks (and road markings) on accident frequency may be influenced by several factors. For example, it is possible that crosswalks give pedestrians a false sense of security leading to pedestrians disproportionately choosing to cross the most apparently dangerous streets only where crosswalks are present. Additionally, the municipal government is most likely to implement crosswalks at intersections with higher baseline risk. In these cases intersections with crosswalks may be associated with elevated accident or injury counts even if the presence of a crosswalk reduces the risk to a given pedestrian who wishes to cross a given street (Mooney et al. 2016). However most studies on accident severity indicate that the absence of road markings and crosswalks tend to lead to more severe crashes in general.

2 Scientific overview

2.1 RESULTS

Effects of the absence of road markings and crosswalks on accident frequency are heterogenous. Whereas some studies on accident frequency indicate a higher crash risk at intersections where road markings or crosswalks are absent, respectively a lower crash risk at intersections with markings or crosswalks, other studies show contrary results. Studies on accident severity however mainly show a higher injury severity at intersections without markings or crosswalks respectively a lower injury severity at intersections with markings or crosswalks.

Some studies on accident frequency show a higher crash risk at intersections where markings or crosswalks are absent compared to crash risk at intersections with present markings or crosswalks. Oh et al. (2008) for example – focusing on bicycle crashes – indicate a significant reduction of crash counts at intersections with crosswalks present: the presence of crosswalks was found to be favourable in the prevention of the probability of bicycle crashes at intersections. Furthermore results of Abdel-Aty and Haleem (2011) – focusing on angle crashes – indicate a decrease of angle-crashes at 3-legged unsignalized T-intersections with markings on the major approach. However, the same study compared to 3-legged unsignalized T-intersections with an existing open median on the major approach and found no statistically difference. In addition, results in the iRAP factsheet indicate a higher crash risk for vehicle occupants, motorcyclists, bicyclists and pedestrians at intersections of poor quality (without road markings) compared to intersection of adequate quality (with road markings), however not statistically significant.

However, other studies show contrary results. Schepers et al. (2001) for example – focusing on bicycle-motor vehicle crashes, where the cyclist has right of way – indicate a significant increase of bicycle-motor vehicle crashes at intersections where red colour high quality markings exist, compared to intersections with no markings. This was also the case for high quality markings only (without using red colour), however not statistically significant. Furthermore results of Koepsell et al. (2002) indicate a significantly higher risk for pedestrian-motor vehicles crashes (involving older pedestrians) at intersections with marked crosswalks compared to intersections with no crosswalks. Specifically, a 2.1-fold increase in risk was associated with the presence of a marked crosswalk. While the risk at signalized or stop-controlled intersections with marked crosswalks was only a bit higher, a 3.6-fold increase in risk was found for uncontrolled intersections with marked crosswalks. Moreover results of Mooney et al. (2016) indicate a significant increase of injury counts at intersections with present crosswalks connecting all corners and present crosswalk connecting some corners compared to intersection with no crosswalks.

Most studies on injury severity report higher injury severity at intersections without markings or crosswalks, and a lower injury severity at intersections with markings or crosswalks. Haleem and Abdel-Aty (2010) for example indicate that having no stop lines on the minor approach significantly increases injury severity when compared to having stop lines on the minor approach. In detail it was found that having no stop lines on the minor approach increases severity by 1.7% when compared to having stop lines. In addition results of Haleem et al. (2015) indicate a significant reduction in pedestrian injury severity at intersections with standard crosswalks. Specifically, standard crosswalks were associated with 1.36% reduction in severe pedestrian injuries. Hanson et al. (2013) indicate that only intersections with crosswalks and controls significantly reduce injury severity, however compared to sites not located at intersections (without control and crosswalk): a somewhat lower severity of injuries at intersections with crosswalk and control was found compared to sites not located at junctions (without control and crosswalk). Junctions with crosswalks only, were found to increase injury severity compared to sites not located at junctions (without control and crosswalk), although not statistically significant.

The studies focusing on the behavior of drivers or pedestrians mostly showed negative effects for the absence of road markings and crosswalks on road safety. Gawade et al. (2014) – focussing on the crossing behaviour of pedestrians – indicate an increase of not crossing on crosswalks at junctions where crosswalks were absent on one side compared to junctions where crosswalks were present on all sides, although results were not statistically significant. However also a not statistically significant decrease of crossing on red at junctions, where crosswalks were absent on one side compared to junctions where crosswalks were present on all sides, was found. Moreover results of Mitman et al. (2008) – focusing on the behaviour of drivers at junctions – indicate significant less immediate yields of drivers for crossing pedestrians at junctions (with 2 and 4 or more lanes) with unmarked crosswalks compared to junctions with marked crosswalks. Pedestrians on the marked crosswalk were more likely than pedestrians on the unmarked crosswalk to have drivers immediately yield the right-of-way to them.

Table 1 illustrates the results of the vote-count analysis. Results show, that the lack of road markings and crosswalks may lead to more severe crashes. Regarding accident frequency, variable (even mostly negative) effects for the presence of road markings and crosswalks can be observed.

Table 1 Results of the vote-count analysis

	Total number of effects tested	Result (number of effects)*			Result (% of effects)	
		↗	-	↘	↗	↘
Accident Frequency**	**13**	**6**	**6**	**1**	**86%**	**14%**
Presence of road markings	3	1	2	0	100%	0%
Absence of road markings	4	0	4	0	-	-
Presence of crosswalk	6	5	0	1	83%	17%
Absence of crosswalks	0	0	0	0	-	-
Accident Severity**	**8**	**1**	**5**	**2**	**33%**	**67%**
Presence of road markings	0	0	0	0	-	-
Absence of road markings	1	1	0	0	100%	0%
Presence of crosswalks	5	0	3	2	0%	100%
Absence of crosswalks	2	0	2	0	-	-

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)
**Since exposures differ, the summarized effects for accident frequency and accident severity can't be interpreted as main results.

2.2 DESCRIPTION OF AVAILABLE STUDIES

2.2.1 Analysis of study designs and methods

Overall 10 high quality studies and 1 iRAP factsheet on the absence of road markings and crosswalks were selected and coded. Most of the studies (Abdel-Aty and Haleem 2011, Schepers et al. 2011, Koepsell et al. 2002, Mooney et al. 2016, Oh et al. 2008) focused on accident frequency and 3 studies (Haleem and Abdel-Aty 2010, Haleem et al. 2015, Hanson et al. 2013) focused on accident severity. Moreover 2 studies (Gawade et al. 2014, Mitman etal. 2008) focused on the behaviour of drivers or pedestrians which also indicated effects regarding road safety. In order to examine the relationship between the absence of road markings and crosswalks and outcome indicators, most studies deployed multivariable statistical models (i.e. negative binomial, probit etc.) as a method of examining the topic and controlled for other geometrical characteristics and traffic flow or pedestrian flow as well. 2 studies used a case-control design.

Studies on accident frequency used mostly negative binomial regression models (Abdel-Aty and Haleem 2011, Schepers et al. 2011, Mooney et al. 2016). In the 2 studies on accident severity, binary probit and mixed/multivariate binomial logit models were developed. Studies focusing on the behaviour of drivers and pedestrians deployed logistic regression models or used a case-control design. Studies focusing on the effects of absent road markings mainly analysed motor-vehicle crashes, while studies focusing on the effect of absent crosswalks on road safety mostly analysed pedestrian crashes. Most research has been done in the United States. Overall 8 studies were carried out there. But also the Netherlands (1 study) and South Korea (1 study) were part of the examination.

Table 2 illustrates an overview of the main features of coded studies (sample, method, outcome and results).

Table 2 Description of coded studies

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
Abdel-Aty and Haleem, 2011, United States	Observational, negative binomial model, data of 2475 unsignalized junctions	Regression analysis between junction characteristics and angle-crash occurrence (3-legged junctions where marking exists on the major approach)	3-legged junctions where an open median exists on the major approach	Focus on angle crashes and 3-legged (and 4-legged) junctions
Haleem and Abdel-Aty, 2010, United States	Observational, binary probit model, data of 243 unsignalized junctions	Regression analysis between junction characteristics and injury severity (3-legged junctions where no stop line exists on the minor approach)	3-legged junction where a stop line exists on the minor approach	Focus on 3-legged (and 4-legged) junctions Focus on injury severity
Schepers et al., 2011, Netherlands	Observational, negative binomial regression analysis, data of 540 junctions	Regression analysis between junction characteristics and bicycle-motor vehicle crashes (junctions with high quality markings and red colour and high quality markings)	Junctions with no high quality marking or red colour	Focus on bicycle-motor vehicle crashes (where the cyclist has right of way)

Author, Year, Country	Sample, method/design and analysis		Reference group	Additional information on analysis
iRAP, 2013, -	Factsheet, risk factors with regard to different road users (car occupants, motorcyclists, bicyclists, pedestrians)	Risk ratio / Relative risks (junctions with poor quality)	Junctions with adequate quality	Risk factors / relative risks
Gawade et al., 2014, United States	Observational, multinomial logistic regression, data of 65 junctions	Regression analysis between junction (and pedestrian) characteristics (junctions where crosswalks are absent on one side)	Junction where crosswalks are present on all sides	Focus on pedestrian behaviour (crossing on crosswalk, crossing on Red)
Haleem et al., 2015, United States	Observational, mixed logit model, data of 3038 pedestrian crashes	Regression analysis between junction characteristics and injury severity	–	Focus on pedestrian crashes and on unsignalized (and signalized) junctions Focus on injury severity
Hanson et al., 2013, United States	Observational, Case-control, multivariate binomial logit model, data of 2351 crashes	Regression analysis between junction characteristics and injury severity; 2 models: pedestrian fatalities vs. all other injuries (1); fatalities and incapaciting injuries vs. all other less-serious-injury outcomes as the control (2)	No control, crosswalk or junction	Focus on injury sevrity
Koepsell et al., 2002, United States	Observational, Case-control, data of 282 urban junctions (cases) and 564 control sites	Case control design	–	Focus on pedestrian-motor vehicle crashes (involving older pedestrians)
Mitman et al., 2008, United States	Observational, Matched, Case-control, data of 6 junctions	Case control design	–	Focus on driver and pedestrian behaviour
Mooney et al., 2016, United States	Observational, negative binomial model, data of 532 junctions	Regression analysis between junction characteristics and injury severity (junctions with present crosswalk)	Junction with no crosswalk	Focus on injury severity of pedestrians
Oh et al., 2008, South Korea	Observational, poisson regression model, data of 151 signalized urban junctions	Regression analysis between junction characteristics and crash occurence (bicycle crashes)	–	Focus on bicycle crashes

2.3 CONCLUSION

Studies on the effect of the absence of road markings and crosswalks on road safety identified in the international literature focus on both accident frequency and accident severity.

The results of the studies on accident frequency are somewhat heterogenous. Some studies on accident frequency indicate a higher crash risk at junctions where road markings or crosswalks were absent and a lower crash risk at junctions with markings or crosswalks, whereas other studies show contrary results.

Studies on accident severity mainly show a (significant) higher injury severity at junctions without markings or crosswalks and a (significant) lower injury severity at junctions with markings or crosswalks. Also studies focusing on the behaviour of drivers or pedestrians mostly showed negative effects for the absence of road markings and crosswalks on road safety.

Summarizing, the absence of road markings and crosswalks at junctions tend to lead to more severe crashes (i.e. an increase to injury severity). Regarding crash risk, rather heterogenous results for the absence of road markings and crosswalks at junctions were found.

3 Supporting document

3.1 METHODOLOGY

3.1.1 Literature Search strategy

Literature search was conducted separately for the absence of road markings and the absence of marked crosswalks in March and April 2016. It was carried out for the two topics in three databases with similar search strategies. Following databases were browsed through during the literature search: 'Scopus', 'Science Direct' and 'TRID'. Detailed search terms, as well as their linkage with logical operators and combined queries are shown in the following tables. The study scope did not exclude countries or source types like "Journal" or "Project". In some of the searches remaining studies were limited to subject areas (e.g. "Engineering"). Out of the overall 1143 potentially eligible studies (both topics), after screening the abstracts of these 1143 studies only from 136 studies the full-text were obtained and only 6 were coded and included in the synopsis. An additional 5 studies were identified due to other already known or during the literature search occasionally (e.g. via Google) found studies as well as studies found in the literature search for other topics and including effects for the absence of road markings and crosswalks. The reference lists of the studies were only partly checked.

Table 3 Literature search strategy absence of road markings, database: Scopus

search no.	search terms / operators / combined queries	hits
#1	(TITLE-ABS-KEY ("markings" OR "absence" OR "risk" OR "regression" OR "pedestrian" OR "crash") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	**20,729**
#2	(TITLE-ABS-KEY ("markings" OR "risk" OR "crash" OR "regression") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	**13,144**
#3	(TITLE-ABS-KEY ("crash" OR "markings" AND "risk" OR "regression") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	**508**
#4	(TITLE-ABS-KEY ("markings" OR "line" AND "Risk" OR "crash") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989 AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "SOCI"))	**165**

Table 4 Literature search strategy absence of marked crosswalks, database: Scopus

search no.	search terms / operators / combined queries	hits
#1	(TITLE-ABS-KEY ("crosswalk" OR "risk" OR "regression" OR "pedestrian" OR "crash" OR "contributory") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	**13,909**
#2	(TITLE-ABS-KEY ("crosswalk" AND "risk" OR "regression" OR "pedestrian" OR "crash") AND TITLE-ABS-KEY ("intersection" OR "junction")) AND PUBYEAR > 1989	**276**

Table 5 Literature search strategy absence of road markings, database: ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	pub-date > 1989 and "markings" AND "intersection" AND "risk"	**1,597**
#2	pub-date > 1989 and "markings" AND "intersection" AND "Crash"	**484**
#3	pub-date > 1989 and "markings" AND "intersection" AND "risk" AND "Crash"	**359**
#4	pub-date > 1989 and "markings" AND "intersection" AND "risk" AND "Crash"[All Sources(Engineering,Environmental Science,Psychology,Social Sciences)].	**325**

Table 6 Literature search strategy absence of marked crosswalks, database: ScienceDirect

search no.	search terms / operators / combined queries	hits
#1	pub-date > 1989 and "crosswalk" AND "intersection" AND "risk" OR "crash"	**415**
#2	pub-date > 1989 and "crosswalk" AND "intersection" AND "risk" OR "crash"[All Sources(Engineering,Environmental Science,Psychology,Social Sciences)]	**358**
#3	pub-date > 1989 and "zebra" OR "crosswalk" AND "intersection" AND "risk" AND "crash"[All Sources(Engineering,Environmental Science,Psychology,Social Sciences)].	**254**

Table 7 Literature search strategy absence of road markings, database: TRID

search no.	search terms / operators / combined queries	hits
#1	"markings" and "intersection" and "safety"	**366**
#2	"markings" and "intersection" and "risk"	**61**

Table 8 Literature search strategy absence of marked crosswalks, database: TRID

search no.	search terms / operators / combined queries	hits
#1	"crosswalk" AND "intersection" AND "risk"	**54**

Table 9 Results Literature Search absence of road markings

Database	**Hits**
Scopus (remaining papers after several limitations/exclusions)	165
ScienceDirect	325
TRID	61
Additional studies	2
Total number of studies to screen title/ abstract	**553**

Table 10 Results Literature Search absence of marked crosswalks

Database	**Hits**
Scopus (remaining papers after several limitations/exclusions)	276
ScienceDirect	254
TRID	54
Additional studies	6
Total number of studies to screen title/ abstract	**590**

The final 11 studies included in the synopsis indicate that the topic has not been investigated to a great extent. Studies selected to code were prioritized as follows, however all studies codable and suitable for the topic were coded.

- Prioritizing Step A (most recent studies)
- Prioritizing Step B (Journals over conferences and reports)
- Prioritizing Step C (Prestigious journals over other journals and conference papers)

No "grey" literature was examined. No meta-analyses were found.

3.1.2 Exploratory analysis of results

Table 11 presents an overview of the main outcomes of the coded studies.

Table 11 Main outcomes of coded studies for absence of road markings and crosswalks

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
Abdel-Aty and Haleem, 2011, United States	Existance of marking on the major approach	Crash count (angle-crashes)	–	r=-0,3739, p=0,2248	Non-significant negative effect of markings on the major approach on occurrence of angle-crashes at 3-legged unsignalized T-intersections (decrease of angle-crashes)
Haleem and Abdel-Aty, 2010, United States	No stop line exists on the minor approach (absence of stop line)	Injury severity	↗	r=0,1133, p=0,0718	Significant negative effect (at the 90% confidence) of absent stop lines on the minor approach on injury severity (compared to having stop lines increase of injury severity by 1,7%)
Schepers et al., 2011, Netherlands	High quality markings	Crash count (bicycle-motor vehicle crashes, where the cyclist has right of way)	–	r=0,55, p=0,112	Non-significant positive effect of high quality markings on crash occurrence (increase of bicycle-motor vehicle crashes)
	Red colour and high quality markings	Crash count (bicycle-motor vehicle crashes, where the cyclist has right of way)	↗	r=0,93, p <0,01	Significant positive effect of red colour and high quality markings on crash occurrence (increase of bicycle-motor vehicle crashes)
iRAP, 2013, -	Poor intersection quality	Crash count / vehicle occupant	–	RR=1,2	Non-significant higher crash risk for vehicle occupants at intersections with poor quality compared to intersections with adequate quality
	Poor intersection quality	Crash count / motorcyclist	–	RR=1,2	Non-significant higher crash risk for motorcyclists at intersections with poor quality compared to intersections with adequate quality
	Poor intersection quality	Crash count / bicyclist	–	RR=1,2	Non-significant higher crash risk for bicyclists at intersections with poor quality compared to intersections with adequate quality
	Poor intersection quality	Crash count / pedestrian	–	RR=1,2	Non-significant higher crash risk for pedestrians at intersections with poor quality compared to intersections with adequate quality

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
Gawade et al., 2014, United States	Crosswalk absent on one side of intersection	Pedestrian (cyclist) behaviour – not crossing on crosswalk	–	r=0,690	Non-significant positive association of crosswalk absent on one side of the intersection and not crossing on crosswalk frequency (increase of not crossing on crosswalks)
	Crosswalk absent on one side of intersection	Pedestrian (cyclist) behaviour – crossing on red	–	r=-0,2180	Non-significant negative association of crosswalk absent on one side of the intersection and crossing on red frequency (decrease of crossing on red)
Haleem et al., 2015, United States	Presence of standard crosswalk	Injury severity	↘	r=-0,743, p=0,006	Significant negative association between presence of standard crosswalk and injury severity (reduction in pedestrian injury severity Standard crosswalks are associated with 1.36% reduction in pedestrian severe injuries.
Hanson et al., 2013, United States	No presence of crosswalk (intersection only) – model 1	Injury severity	–	OR=0,829, p=0,442	Non-significant reduction in injury severity compared to no control, crosswalk or intersection
	Presence of crosswalk – model 1	Injury severity	–	OR=0,837, p=0,674	Non-significant reduction in injury severity compared to no control, crosswalk or intersection
	Presence of crosswalk and traffic controls – model 1	Injury severity	–	OR=0,894, p=0,578	Non-significant reduction in injury severity compared to no control, crosswalk or intersection
	No presence of crosswalk (intersection only) – model 2	Injury severity	–	OR=0,879, p=0,416	Non-significant reduction in injury severity compared to no control, crosswalk or intersection
	Presence of crosswalk – model 2	Injury severity	–	OR=1,034, p=0,886	Non-significant increase in injury severity compared to no control, crosswalk or intersection
	Presence of crosswalk and traffic controls – model 2	Injury severity	↘	OR=0,772, p=0,053	Significant reduction in injury severity compared to no control, crosswalk or intersection
Koepsell et al., 2002, United States	Presence of marked crosswalk	Crash count	↗	OR=2,1	Significant higher risk for pedestrian-motor vehicles crashes (involving older pedestrians) at intersections with marked crosswalks

Author, Year, Country	Exposure variable	Outcome variable / Outcome type	Effects		Main outcome - description
	Presence of marked crosswalk – signalized or stop-controlled	Crash count	↗	OR=1,2, p=0,03	Significant higher risk for pedestrian-motor vehicles crashes (involving older pedestrians) at signalized or stop-controlled intersections with marked crosswalks
	Presence of marked crosswalk - uncontrolled	Crash count	↗	OR=3,6, p=0,03	Significant higher risk for pedestrian-motor vehicles crashes (involving older pedestrians) at uncontrolled intersections with marked crosswalks
Mitman et al., 2008, United States	Unmarked crosswalk – 2 lanes	Immediate yields of drivers (count, average number)	↗	Absoulte difference= -0,30 (unmarked – marked)	Significant less immediate yields of drivers for crossing pedestrians
	Unmarked crosswalk –4 or more lanes	Immediate yields of drivers (count, average number)	↗	Absoulte difference= -0,70 (unmarked – marked)	Significant less immediate yields of drivers for crossing pedestrians
Mooney et al., 2016, United States	Crosswalk presence connecting all corners	Pedestrian injury count	↗	Relative Difference = 80%	Significant increase of injury counts when crosswalk connecting all corners is present
	Crosswalk presence connecting some corners	Pedestrian injury count	↗	Relative Difference = 93%	Significant increase of injury counts when crosswalk connecting some corners is present
Oh et al., 2008, South Korea	Presence of crosswalks	Crash count	↘	r=2,17	Significant reduction of crash counts (bicyle crashes) when crosswalks are present

*Significant effects on road safety are coded as: positive (↘), negative (↗) or non-significant (–)

3.2 FULL LIST OF STUDIES

3.2.1 List of studies

A detailed list of studies coded is presented below:

Abdel-Aty, M. / Haleem K. (2011): Analyzing angle crashes at unsignalized intersections using machine learning techniques. Accident Analysis and Prevention 43, pp. 461-470.

Haleem, K. / Abdel-Aty, M. (2010): Examining traffic crash injury severity at unsignalized intersections. Journal of Safety Research 41, pp. 347-357.

Schepers, J.P. / Kroeze, P.A. / Sweers, W. / Wüst, J.C. (2011): Road factors and bicycle-motor vehicle crashes at unsignalized priority intersections. Accident Analysis and Prevention 43, pp. 853-861.

International Road Assessment Programme (2013). Road Attribute Risk Factors. Intersection Quality. International Road Assessment Programme (iRAP).

Gawade, M. / Kourtellis, A. / Lin, P. (2014): Multivariate Analysis on Factors Influencing Pedestrian and Bicycle Safety. TRB 2014 Annual Meeting.

Haleem, K. / Alluri, P. / Gan, A. (2015): Analyzing pedestrian crash injury severity at signalized and non-signalized locations. Accident Analysis and Prevention 81, pp. 14-23.

Hanson, C.S. / Noland, R.B. / Brown C. (2013): The severity of pedestrian crashes: an analysis using Google Street View. Journal of Transport Geography Vol. 33, pp. 42-53.

Koepsell, T. / McCloskey, L. / Wolf, M. / Moudon, A.V. / Buchner, D. / Kraus, J. / Patterson, M. (2002): Crosswalk Markings and the Risk of Pedestrian-Motor Vehicle Collisions in Older Pedestrians. JAMA - The Journal of the American Medical Association, November 6, 2002 - Vol. 288, No 17.

Mitman, M.F. / Ragland, D.R. / Zegeer, C.V. (2008): The Marked Crosswalk Dilemma: Uncovering Some Missing Links in a 35Year Debate. TRB 2008 Annual Meeting.

Mooney, S.J. / DiMaggio, C.J. / Lovasi, G.S. / Neckerman, K.M. / Bader, M.D.M. / Teitler, J.O. / Sheehan, D.M. / Jack, D.W. / Rundle, A.G. (2016): Use of google street view to assess environmental contributions to pedestrian injury. American Journal of Public Health Vol. 106, Issue 3, pp. 462-469.

Oh, J. / Jun, J. / Kim, E. / Kim, M. (2008): Assessing Critical Factors Associated with Bicycle Collisions at urban signalized intersections. TRB 2008 Annual Meeting.

3.2.2 References on further background information

UIIG – Unsignalized intersection improvement guide (2015): Types of Problems. Inadequate guidance for motorists. In: http://www.ite.org/uiig/problems.asp#guidance (28.07.2016)

Department for Traffic (2006): Traffic Signs Manual. Chapter 8. Traffic Safety Measures and Signs for Road Works and Temporary Situations. Part 2: Operations.Queen's Printer and Controller of HMSO. London.