Accident Analysis and Prevention 62 (2014) 331–340

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

A conceptual framework for road safety and mobility applied to cycling safety

Paul Schepers[a,b,*], Marjan Hagenzieker[b,c], Rob Methorst[a], Bert van Wee[d], Fred Wegman[b,c]

[a] Ministry of Infrastructure and the Environment, The Netherlands
[b] SWOV Institute for Road Safety Research, The Netherlands
[c] Delft University of Technology, Civil Engineering and Geosciences, The Netherlands
[d] Delft University of Technology, Transport and Logistics Group, The Netherlands

ARTICLE INFO

Article history:
Received 7 December 2012
Received in revised form 17 February 2013
Accepted 12 March 2013

Keywords:
Road safety
Bicycle
Cycling safety
Land use
Infrastructure
Models
Conceptual model
Framework

ABSTRACT

Scientific literature lacks a model which combines exposure to risk, risk, and the relationship between them. This paper presents a conceptual road safety framework comprising mutually interacting factors for exposure to risk resulting from travel behaviour (volumes, modal split, and distribution of traffic over time and space) and for risk (crash and injury risk). The framework's three determinants for travel behaviour are locations of activities; resistances (generalized transport costs); needs, opportunities, and abilities. Crash and injury risks are modelled by the three 'safety pillars': infrastructure, road users and the vehicles they use. Creating a link in the framework between risk and exposure is important because of the 'non-linear relationship' between them, i.e. risk tends to decrease as exposure increases. Furthermore, 'perceived' risk (a type of travel resistance) plays a role in mode choice, i.e. the perception that a certain type of vehicle is unsafe can be a deterrent to its use. This paper uses theories to explain how the elements in the model interact. Cycling is an area where governments typically have goals for both mobility and safety. To exemplify application of the model, the paper uses the framework to link research on cycling (safety) to land use and infrastructure. The model's value lies in its ability to identify potential consequences of measures and policies for both exposure and risk. This is important from a scientific perspective and for policy makers who often have objectives for both mobility and safety.

1. Introduction

This paper introduces a conceptual framework for road safety and mobility and applies it to cycling safety to exemplify its application. One of the major problems of road safety research is that most of it does not have a strong theoretical basis. The lack of such a basis makes it difficult to design suitable studies and interpret findings (Elvik, 2004). Current road safety models are focused mainly on risk. Traffic and transport literature offers models for travel behaviour that help to explain exposure to risk. To the best of our knowledge, there is no framework that combines exposure to risk (resulting from travel behaviour) and risk in current scientific literature. Such a framework would be useful for both road safety researchers and policy makers for identifying the potential effects of measures and policies. Because road crashes result from both exposure to risk (hereafter referred to as *exposure*) and risk, a model comprising both factors as well as the interactions between them would help researchers acquire a broader insight into potentially relevant safety effects. This paper presents a conceptual framework for road safety incorporating factors for determining exposure and risk, and the relationship between these two.

To explain the framework and its usefulness, it is applied to the question of how cycling safety is affected by land use and infrastructure characteristics (road networks, road sections, and intersections). Cycling is an area where governments typically have targets for both mobility and road safety. Governments promote cycling as it is an environmentally sustainable mode of transport and is associated with public health benefits (see e.g. De Hartog et al., 2010; Heinen et al., 2011). Adapting land use and infrastructure is a means for governments to improve cycling safety and increase bicycle use. However, research regarding cyclist mobility and cyclist safety is not yet well connected. There are review studies that describe how the built environment affects bicycle use (e.g. Heinen et al., 2010) and how road factors affect cycling safety (e.g. Reynolds et al., 2009), but only few link both factors. This link is important for policy makers and research, because ignoring one of the two factors, or the interaction between them, might lead to

---

* Corresponding author at: Ministry of Infrastructure and the Environment, The Netherlands. Tel.: +31 887982457.
E-mail address: paul.schepers@rws.nl (P. Schepers).

0001-4575/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.aap.2013.03.032

an over- or underestimation of the safety effects of candidate policy options, and result in 'erroneous' policies.

Section 2 of this paper describes the conceptual road safety framework, and Section 3 its application to cycling (safety) and its link with land use and infrastructure characteristics. Both sections include subsections for risk, travel behaviour and their interaction. Section 4 exemplifies the model's application by applying it to the low-cost measure of converting one-way to two-way cycle tracks, with the results discussed in Section 5.

2. A conceptual road safety framework

Consistent with Asmussen and Kranenburg (1982), our conceptual framework contains factors determining exposure to risk (resulting from travel behaviour), crash risk, and injury risk (or injury severity). It combines Van Wee's (2009) passenger transport model for exposure to risk with the model of the three traffic safety pillars for risk (Othman et al., 2009) (see Fig. 1). This section introduces the conceptual road safety framework. After an explanation of the decisions underlying its development, three subsections focus on travel behaviour (Section 2.1.1), and risk (Section 2.1.3), and the relationship between exposure and risk (Section 2.1.2). Section 2.1.4 describes the demarcation needed to reduce the framework's complexity. Section 2.2 uses theories and concepts to explain the interaction of the framework's elements.

A conceptual framework or model is an abstraction or simplification of reality to help us better understand real world systems, facilitate communication and integrate knowledge across disciplines (Heemskerk et al., 2003; Ford, 2009). These goals are best served by models with a limited number of factors, such as the Van Wee (2009) model and the three traffic safety pillars (Othman et al., 2009). Both models have mutually interacting factors, recognizing that accidents can result from combinations of interacting variables. In contrast, crash-phase models such as Heinrich's Domino Theory (Heinrich, 1931) assume that accidents result from a series of events or circumstances and are thus preventable by eliminating one of the causes in the linear sequence. According to Toft et al. (2012), because accidents often result from combinations of mutually interacting variables, modelling approaches for crash research need to shift from linear models (such as crash phase models) to non-linear models (such as the model described in this paper).

People are exposed to risk in traffic because they travel and because there are dangers present in traffic. As yet, we have not yet managed to achieve danger-free travel. The measures used in the road safety literature for exposure to risk are directly linked to travel behaviour, e.g. kilometres travelled and Annual Average Daily Traffic (AADT) (what the best measure is depends on the issue being studied, see Hakkert and Braimaister, 2002). Therefore, travel behaviour and exposure to risk have been combined in the framework in one box. Similarly, crash and injury risk are put in one box although both are generally accepted as distinct dimensions of the road safety problem (Rumar, 1999). This is done because the links to other elements in the model are similar, and it reduces the model's complexity. The model does not include the post-crash phase in which, for instance, the emergency medical system is relevant to the injury risk. Separate boxes for crash and injury risk would have to be inserted if elements relating to the post-crash phase were to be included in the model. The model is not a chronologically organized crash-phase model, but there is order in the sense that travel decisions taken before traffic participation (the focus of the upper part of the model) result in exposure to risk during traffic participation (the lower part of the model).

2.1. Description of the framework

2.1.1. Travel behaviour

Travel behaviour literature commonly distinguishes between traffic volumes, modal split and distribution of traffic over time and space (Van Wee, 2009). Van Wee (2009) developed a model for passenger transport that contains elements determining travel behaviour: locations of activities, transport resistances (generalized transport costs), and needs, opportunities and abilities. People travel between *Locations of activities* to perform activities such as living, working, and shopping. Travel takes money and time and incurs non-monetary' costs such as discomfort, which together make up *Travel resistance*. Perceived risk, which is also a type of resistance, is modelled explicitly by an arrow from *Risk* to *Travel resistance*. Besides locations and travel resistance, travel behaviour is also affected by *Needs, opportunities, and abilities (NOA)*; for instance the need for active travel, the possession of a driving license and car, or the physical fitness needed to walk and cycle. All three categories (locations, resistance, and NOA) are influential in all directions. *Travel behaviour* decisions sum up to traffic volumes, modal split, and the distribution of traffic over time and space (Van Wee and Maat, 2003). Travel decisions taken by individuals before traffic participation have also been called 'strategic and lifestyle decisions' (Michon, 1985; Hatakka et al., 1999): mode choice and moving to a new home, etc. These decisions result in exposure to risk during traffic participation. Behaviour during traffic participation has been described as tactical and operational behaviour (Michon, 1985).

2.1.2. The link between exposure and risk

The model comprises an arrow from *Exposure to risk* to *Risk*, because exposure affects risk. Most empirical studies show that risk decreases as exposure increases (Elvik, 2009). An arrow from *Risk* to *Exposure to risk* is included to indicate that traffic participants are exposed to risks only to the extent that risks are present. The model also includes a feedback loop from *Risk* to *Travel resistance*. Risk may affect perceived risk which, in turn, can cause travellers to shift to other modes or even avoid trips (Heinen et al., 2010; Van Wee et al., in press).

2.1.3. Risk

Crash risk results from interaction between three elements, sometimes called the 'three traffic safety pillars': road user(s), vehicle(s), and infrastructure (e.g. Othman et al., 2009). Similarly, epidemiologists use the terms host, agent, and environment (Haddon, 1980). Note that Haddon's definition of environment also includes the social environment. Single-vehicle crashes may involve only one vehicle and one road user, whereas 'conflicts' involve an interaction between several vehicles and road users (for a more detailed model that includes the interaction between road users, see Houtenbos, 2008). Depending on the energy that is exchanged between road users, vehicles and infrastructure, crashes may result in injuries with varying levels of severity. Crashes may be fatal when forces transferred to victims exceed their biomechanical tolerance. This tolerance depends on age, health status, stature and other characteristics of road users involved in a crash (Corben et al., 2004). The framework provides for two-way arrows between *Risk* on the one hand and *Infrastructure*, *Vehicles* and *Road Users* on the other hand. The skills and capabilities of road users, and the quality of vehicles and infrastructure can be improved, e.g. for road users – education and requirements such as licence age limits and health requirements (Elvik and Vaa, 2009). Reversing the direction of the arrows: high risks may lead to policies to reduce these risks, e.g. EuroNCAP for cars (EuroNCAP, 2012) and EuroRAP for roads

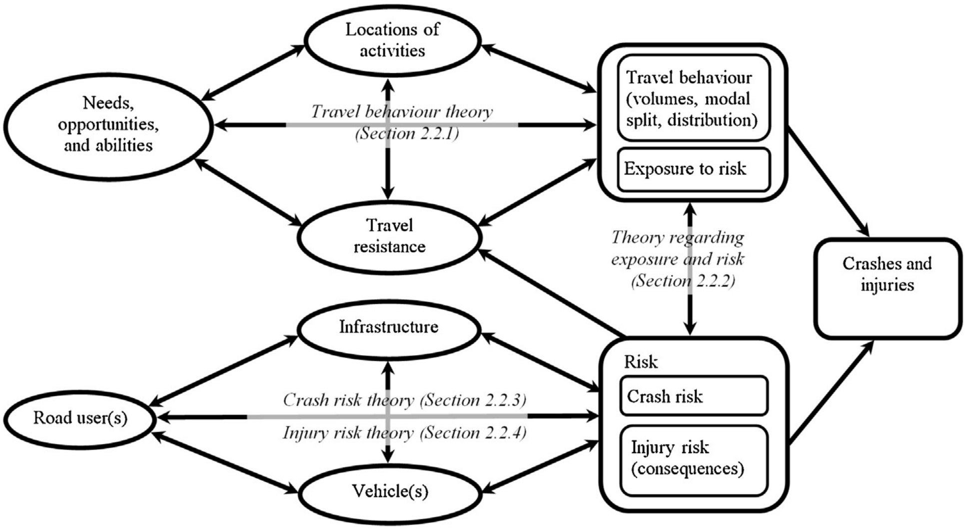

Fig. 1. Conceptual framework for road safety, including exposure and risk (sections describing the theories are referred to in parenthesis).

(EuroRap, 2011) (for effectiveness studies, see e.g. Lie and Tingvall, 2002; Vlakveld and Louwerse, 2011).

2.1.4. Demarcation

In line with systems theory the framework depicts safety as an emergent property that arises when system components interact, but the components are also affected by the environment (Leveson, 2004). Similarly, our framework has several inputs from the environment such as demographics, fuel prices, technological developments, etc. In the interests of reducing the framework's complexity these external influences are not conceptualized. Similarly, the framework does not depict a feedback loop from crashes and injuries to NOA to indicate the effect of injuries on abilities. Relationships that may exist between the model's exposure and risk elements (e.g. between *Infrastructure*, *Travel resistance* and between *Road users* and *NOA*) are excluded for the same reason and to emphasize the impact of differences in timing. Travel decisions taken before traffic participation result in exposure to risk during traffic participation.

2.2. Theories

This section briefly describes in terms of theories and concepts how the elements in the framework interact: travel behaviour theories (Section 2.2.1), theories explaining the link between exposure and risk (Section 2.2.2), crash risk theories (Section 2.2.3), and injury risk theories (Section 2.2.4).

2.2.1. Travel behaviour theories

The dominant theory for explaining travel behaviour is (random) utility maximization (McFadden, 1974). This holds that people maximize their utility, e.g. a trip is made if the (expected) benefits of performing an activity at a location ('locations of activities') exceed the (expected) time, cost and effort of travel ('travel resistance'). Alternative models of bounded rationality have been developed which, without completely abandoning the idea that reason underlies decision-making processes, tend to be more psychologically plausible. For example, Prospect Theory accounts for decision heuristics such as loss aversion (Kahneman and Tversky, 1979; Van de Kaa, 2010). Regret theory holds that people wish to avoid the regret that a non-chosen alternative turns out to be more attractive than the chosen one (Chorus et al., 2008). The Theory of Planned Behaviour holds that attitudes towards behaviour, subjective norms and perceived behavioural control together shape an individual's behavioural intentions and behaviours (Ajzen, 1985). Deciding to make a trip may also depend on needs (e.g. driving as a status symbol), opportunities (e.g. having a railway station nearby to go by train), and abilities (e.g. being healthy enough to cycle) (see e.g. Vlek et al., 1997).

The theories mentioned so far help explain the links between determinants for travel behaviour (needs, resistance, locations). They also help explain the other links between the factors in the upper part of the framework. For instance people who greatly appreciate a large city's cultural and social activities (needs) will prefer living in a large city (location). People desiring safe and fast travel (travel needs/preferences) may seek a dwelling near a large railway station (location). A theory that helps to explain the link between locations of activities and NOA is that of time-space geography. It explains the movement of individuals in the spatial-temporal environment with the constraints placed on them by these two factors (Hägerstrand, 1970). For instance, to be able to work with colleagues or eat family dinners together requires several people to be at the same place at the same time. Opportunities to go shopping depend on opening hours, etc. The relationship between locations of activities and resistances can be explained by the 'theory of constant travel time budgets', which holds that, at an aggregate level (e.g. the country or state level), average daily time spent on travel is fairly constant (Mokhtarian and Chen, 2004). For example, this means that if a new motorway, railway, or cycle path is opened which reduces travel times (i.e. decreased resistance), some people may consider changing residential location or destinations such as the job location. Constant travel time budgets can be explained by utility theory. Besides seeking an optimal balance between time for activities and related travel, people compare the marginal disutility of extra travel time or additional trips with the marginal benefits of related activities (Van Wee et al., 2006).

2.2.2. Theories explaining the link between exposure and risk

The framework depicts a relationship between exposure and risk and shows an arrow from *Risk* to *Travel resistance*. Perceived risk, which is weakly correlated to actual risk, influences travel behaviour (Vlakveld et al., 2008). The perception that a certain type of vehicle such as a bicycle is unsafe can be a deterrent to its use (Heinen et al., 2010). An important concept to explain the influence of exposure on risk is the so called 'non-linearity of risk'. It holds that the number of crashes at a given road section or intersection increases proportionally less with the increase in the volume at that facility (at least above a certain amount of traffic that results in interactions between road users). There are possible explanations related to road user interaction and infrastructure, but most theoretical investigation into the relationship between flow and safety seems to lack detail (Ardekani et al., 2000). One explanation is that the second and subsequent vehicles of a platoon may have a much lower chance of being involved in a right-angle collision at a signalized intersection than the first vehicle (Ardekani et al., 2000). Other researchers have suggested that improved infrastructure may be one of the explanations for the non-linearity of risk, e.g. Jensen (1999) argues that cities are designed to meet different travel behaviour. Similarly, at the individual level it has been found that drivers travelling more kilometres have lower crash rates per kilometre. An explanation for this is that these drivers accumulate most of their kilometres on freeways or other divided multilane highways where crash rates are lower (Janke, 1991).

2.2.3. *Crash risk theories*

The interaction between vehicles, road infrastructure and road users plays a role in crash risk, which can be explained using theories from physics and social sciences. The interaction between road users and roads is often called ‘human factors’, while the interaction between road users and vehicles is labelled as ‘man–machine factors’ (Birth et al., 2009). Four types of so called ‘functional driver behaviour models’ have the ability to describe how the road environment and vehicles can be adapted to fit road users’ capabilities in order to reduce crash risk: perception models, cognitive models, workload models, and motivational models (Michon, 1985; Ranney, 1994; Weller and Schlag, 2007). The first three describe what road users are *able* to handle; motivational models explain what drivers are *motivated* to do. Physical factors based on physics help to explain the interaction between vehicles and infrastructure, e.g. friction between tyres and the road surface to enable steering and braking (Elvik, 2006) and superelevation to negotiate a curve (Aram, 2010).

2.2.4. *Injury risk theories*

Theories from physics, such as Newtonian mechanics, and medicine (Sobhani et al., 2011) have been used to explain injury risk, i.e. the severity of injuries incurred in a crash. The energy damage model, often attributed to Gibson (1961), is based on the supposition that damage (injury) is a result of an incident energy whose intensity at the point of contact with the recipient exceeds the threshold of the recipient (Viner, 1991; Toft et al., 2012). Crash energy may be released when there is a failure of hazard control mechanisms such as barriers. In road traffic it is the kinetic energy produced by the movement of people and vehicles that is a potential crash energy. Mass differences are crucial when motor vehicles and vulnerable road users collide. Energy may be exchanged between vehicles, road users, and infrastructure, meaning that it affects all three safety pillars. Crashes may be fatal when forces transferred to victims exceed their biomechanical tolerance, which depends on age, health status, stature, and other factors (Corben et al., 2004).

3. Cycling safety related to land use and infrastructure

To demonstrate the framework’s usefulness, this section applies it to the relationship between cycling safety, and land use and infrastructure characteristics. The framework elements most relevant to this issue are *Locations of activities* (land use), *Travel resistance* (network and road characteristics), and *Infrastructure* (road design). We have searched for scientific literature on cycling and cycling safety, preferably empirically validated or otherwise theoretically feasible, that is suitable for describing different parts of the model.

3.1. *Travel behaviour and exposure*

This section describes cycling travel behaviour (Section 3.1.1.) and the distribution of traffic over time and space (Section 3.1.2). It refers to both motorists and cyclists because modal split and distribution over time and space determine the degree to which cyclists are exposed to (high speed) motorists.

3.1.1. *Cycling travel behaviour (volumes and modal split)*

This section describes studies that relate cycling to land use and infrastructure characteristics. More studies focused on mode choice than on cycling frequency (Heinen et al., 2011). Because the decision to cycle and cycling frequency are strongly interrelated, it was decided not to make any further distinction between them in this section. Land use and infrastructure characteristics affect cycling distances. This is important because the disutility of cycling increases more than proportionally for longer distances, which might be explained by physiological factors and speed (Van Wee et al., 2006). Heinen et al. (2010) conclude from their literature review on bicycle commuting that distance is a daunting factor for cyclists. Land use characteristics which contribute to shorter travel distances, such as a higher population density (e.g. a compact city) and mixed land-use, have been found to affect cycling positively (Heinen et al., 2010).

Resistance is strongly linked to the physical and functional characteristics of infrastructure networks. The following effects on bicycle use for utilitarian purposes (all purposes apart from recreational/leisure purposes) have been found:

- *Road structure density*: According to Southworth (2005), a denser road structure is more suitable for non-motorized transportation because distances are generally smaller. However, neither Moudon et al. (2005) nor Zacharias (2005) found significant empirical evidence that can confirm the influence of the density of roadways and block size on cycling.
- *Bicycle paths*: While Heinen et al. (2010) have found several studies which conclude that more bicycle paths result in a higher share of cycling (e.g. Barnes and Thompson, 2006), they also found studies in which no significant effect was found (e.g. Moudon et al., 2005). Additional infrastructure might make little difference in countries where cycling facilities are more common (Heinen et al., 2010).
- *Number of stops*: Rietveld and Daniel (2004) have found that the number of stops cyclists have to make on their routes is a deterrent to cycling.

3.1.2. *Distribution of traffic over time and space*

Little research has been done on the effect of infrastructure on the distribution of cycling traffic any 24 h period, except perhaps the reluctance of older cyclists to cycle in darkness, which may be influenced by the visual design of infrastructure and the presence of street lighting (Schepers and Den Brinker, 2011). It is obvious that land use (the distribution of activity locations over space) has an effect on the distribution of traffic (including cycling) over time and space. For instance, an entertainment centre may attract young visitors at night. Its location at the edge of town may result in longer average distances between it and the locations of the dwellings of young visitors, resulting in a lower share of cycling and longer cycling distances for those who do cycle. High exposure to dangerous situations such as driving at night at weekend has been found to be a cause of the high crash rate of young novice drivers (Vlakveld, 2005). Similarly, research suggests that youngsters frequently cycle at night and frequently after having consumed alcohol (Reurings, 2010; Schepers and Den Brinker, 2011).

A concept that helps to describe the distribution of traffic over space is ‘street hierarchy’. This affects route choice by manipulating travel times, i.e. resistance (see for more information Hummel, 2001). This concept became very influential after Buchanan (1963) published *Traffic in Towns*. In a hierarchical road structure, lower order roads (access roads in what Buchanan named 'environmental areas') serve access traffic, while higher order roads serve an efficient flow of through motor traffic (through roads such as motorways). In between are distributor or collector roads to distribute traffic from through roads to access roads and vice versa. A motorway network where cyclists are not allowed, with grade separated intersections, reduces cyclists' exposure to high speed motorists. Access roads are designed for low speeds to keep through motor traffic away. A high share of short bicycle trips results in a high number of kilometres being travelled on access roads where exposure to (high speed) motorists is limited. Research shows that the number of bicycle–motor vehicle crashes is indeed high along distributor roads and low on access roads (Berends and Stipdonk, 2009; Schepers et al., 2011). Evaluation studies have not yet addressed the combined effect of a general road hierarchy with bicycle-specific measures such as bicycle bridges and tunnels to alleviate potential safety problems at distributor roads. Depending on how the road network fits the needs of different transport modes, a road hierarchy may affect travel times for drivers and cyclists differently, thereby affecting modal choice. Cyclists may benefit from short cuts where roads are closed for drivers and from being allowed to use one-way streets in both directions, etc. Providing more direct routing for one mode in contrast to the other may increase mode share for the favoured mode (Frank and Hawkins, 2008).

3.2. *The relationship between exposure and risk*

This section describes the relationship between exposure (resulting from travel behaviour) and risk: firstly the effect of exposure on risk (Sections 3.2.1 and 3.2.2) and secondly the effect of (perceived) risk on exposure (Section 3.2.3).

3.2.1. *The effect of bicycle volumes on road safety*

The number of crashes at a given road section or intersection increases proportionally less than the increase in the volume at that facility; the same applies to bicycle–motor vehicle crashes (Brüde and Larsson, 1993; Elvik, 2009) and single-bicycle crashes (Schepers, 2012). Cycling safety research describes the non-linearity of risk as the 'safety in numbers' phenomenon (Jacobsen, 2003). Jacobsen's (2003) explanation is that motorists modify their behaviour when they expect or experience people walking and bicycling. Theories regarding expectancy in traffic which can underpin this are described by researchers such as Houtenbos (2008) and Theeuwes and Godthelp (1995). Others have suggested that improved infrastructure may be one of the explanations for the non-linearity of risk (Brüde and Larsson, 1993; Wegman et al., 2012). The non-linearity of risk implies that cyclists are safer where there are more cyclists. It is difficult to draw conclusions about how road safety in general will be affected because the non-linearity of risk also applies to other modes of transport.

3.2.2. *Modal split and road safety*

Cycling is associated with a considerably higher risk of injury accidents than travel by car (Wegman et al., 2012). One could therefore expect that a modal shift from car to bicycle would have negative effects on road safety in general. However, there are reasons why the effect is limited. The most important one is that after shifting from car driving to cycling, individuals are less hazardous to other vulnerable road users (including cyclists) because of the lower amounts of kinetic energy expended in the event of a crash. A number of studies have accounted for this factor (see for other explanations Schepers and Heinen, 2013).

Using existing Accident Prediction Models (APMs) in which a nonlinear relationship between crashes and volumes is assumed, Elvik (2009) was the first to estimate the road safety effects of shifts from car to bicycle (and walking). His results suggest that if there are very large transfers of trips from motor vehicles to walking or cycling, the total number of accidents may be reduced. His method was recently applied to Dutch data by Schepers and Heinen (2013). Their results suggest that transferring short trips made by cars to bicycles does not change the number of fatalities, but increases the number of serious road injuries. Stipdonk and Reurings (2012) followed a different approach to determine the effect of an exchange over a short period of time, i.e. without adapting infrastructure. Instead of (stochastic) APMs, they applied a deterministic model, assuming a linear relationship between volumes and road crashes. The study results suggest that a modal shift from cars to bicycles leads to a small increase in the number of fatalities and a greater increase in the number of hospitalized casualties. The latter is due to the high numbers of cyclists injured in single-bicycle crashes. Both Stipdonk and Reurings (2012) and Schepers and Heinen (2013) find that effects vary across the age groups. Elderly drivers are safer inside a car than on a bicycle. From a road safety perspective, the car–bicycle shift is, on balance, advantageous for young drivers and disadvantageous for elderly drivers.

Studies on the health effects of a modal shift from short car trips to cycling (e.g. De Hartog et al., 2010) have not yet included the health burden anticipated from an increased number of single-bicycle crash victims. This is because studies that incorporated single-bicycle crashes in estimations of the road safety effects of a modal shift were published only recently (i.e. Stipdonk and Reurings, 2012; Schepers and Heinen, 2013). However, given the large health benefits associated with physical exercise (De Hartog et al., 2010; Oja et al., 2011), it is likely that that health benefits will outweigh the health risks, even if these non-fatal crashes were included.

3.2.3. *The effect of risk on bicycle use*

People, especially non-cyclists (Heinen and Handy, 2012), generally perceive cycling to be less safe than walking, driving a car or using public transport. This would imply that this form of travel resistance is higher for cycling (Elvik and Bjørnskau, 2005). The risk of an accident is a deterrent to cycling (Parkin et al., 2007; Heinen et al., 2010). Research indicates that cyclists prefer dedicated bicycle infrastructure because they perceive it to be safer (Heinen et al., 2010). For instance, Gårder et al. (1998) found an increased volume of cyclists at road sections after cycle tracks had been installed. Vandenbulcke-Plasschaert (2011) suggests that actual and perceived risks of cycling may be one of the factors explaining the high amount of cycling in Flanders in the northern part of Belgium, as compared to Wallonia in the south. The same reasoning may be valid in explaining differences between countries. Rietveld and Daniel (2004) found that safety appears to matter as a component in generalized costs and that it explains part of the variation in the amount of bicycle use in Dutch municipalities. Pucher and Buehler (2008) suggest that safety may affect the compilation of the population of cyclists because women, the elderly and parents of young children appear to be especially sensitive to perceived road safety. This may be another factor that explains differences in safety between different countries, i.e. cyclists in countries with higher amounts of cycling may be more cautious. Finally, the injuries incurred in crashes may affect bicycle use. Ormel et al. (2008) found more than one-third of all hospitalized single-bicycle crash victims cycled less after their accident, because of a combination of physical problems and fear of taking another fall.

3.3. *Crash risk*

This section describes how cycling risk is affected by infrastructure characteristics. The risk of collisions depends on the number of potential conflict points and how well road users are able to handle conflicts. For instance, a roundabout reduces the number of potential conflict points compared to an intersection which has favourable safety effects in general (Elvik, 2004), although the effects found for cyclists are not consistent (Brüde and Larsson, 2000; Dijkstra, 2004; Daniels et al., 2009). Sakshaug et al. (2010) have found a higher number of conflict and interaction types at roundabouts where cyclists are mixed with other vehicles compared to a roundabout with separate cycle crossings. The risk of single-bicycle crashes is influenced by how well cyclists are supported when balancing and steering their bicycles, and avoiding obstacles (Schepers and Klein Wolt, 2012). The abovementioned issues refer to the framework's link of *Infrastructure* to *Road users* (Section 3.3.1) and to *Vehicles* (Section 3.3.2). Human factors theories or ergonomics theories help explain how roads can be designed to fit road users' needs and capabilities (Birth et al., 2009). Theories from physics help to describe how infrastructure can be designed to help cyclists safely balance and steer their bicycles.

3.3.1. *Human factors*

The application of ergonomics theories for optimal cycling safety depends on the context. While a complete overview of applications is outside the scope of this text, this paper gives some examples to show the value of human factor theories for cycling safety.

Theories on perception help understand to what extent road users are able to perceive objects and where the road is going. For example, ambient-focal dichotomy is a powerful theory which describes vision and driving in terms of the visual system as being two parallel streams of processing, labelled the ambient and focal subsystems (Leibowitz and Owens, 1977; Schieber et al., 2008). The proposition is that visual processing proceeds along two parallel streams, one dedicated to visual orientation for the question "Where am I?" (ambient vision) and the other to object recognition and identification for the question "What is it?" (focal vision) (Leibowitz and Post, 1982; Previc, 1998). Drivers use ambient vision to track and minimize instantaneous errors in lane position. They use focal vision to anticipate hazards and future alterations in the course of the road (Donges, 1978). Schepers and Den Brinker (2011) recently used the ambient-focal dichotomy in a study where they showed that the visual design of bicycle facilities plays a role in single-bicycle crashes.

A powerful theory from cognitive psychology is 'expectancy' theory (Theeuwes and Hagenzieker, 1993; Houtenbos, 2008). Concepts such as Self-Explaining Roads (Theeuwes and Godthelp, 1995), geometric consistency (Fitzpatrick et al., 1999), and the Sustainable Safety principle of predictability and recognisability (Wegman and Aarts, 2006) all hold that roads should be designed in line with road users' expectations and such that they create the right expectations. An often-cited violation of expectations that results in errors occurs at priority intersections with two-way bicycle tracks. The risk of bicycle crashes is found to be elevated because drivers entering from the minor road have difficulties in detecting cyclists from the right (in case of right-hand driving) (Räsänen and Summala, 1998; Schepers et al., 2011). Summala et al. (1996) studied drivers' scanning behaviour at T-intersections. Drivers turning right from the minor road scanned the right leg of the T-intersection less frequently and later than those turning left. Their explanation is that drivers turning right focus their attention on cars from the left because those coming from the right pose no threat to them. The visual scanning strategy seems to concentrate on more frequent and major potential dangers (Summala et al., 1996).

Workload models indicate that humans have a limited information processing capacity. Taking into account individuals' capabilities, workload can be either too low ('underload') or too high ('overload') due to the task demands of driving or cycling and double tasks such as mobile phone use (De Waard, 1996; De Waard et al., 2010). A concept linked to road design and related to the probability that some road users will be overloaded is 'complexity'. According to Elvik (2006), the 'law of complexity' holds that the more units of information a road user must attend to, the higher becomes the accident rate. This especially applies to situations subject to time pressure. For instance, older drivers and cyclists are more often involved in left-turning crashes and situations with associated time pressures where traffic from several directions has to be scanned (Goldenbeld, 1992; Davidse, 2007). From the perspective of workload, the opposite of 'complexity' is 'monotony' (Birth et al., 2009) or 'highway hypnosis' – reduced alertness on long, straight roads (SWOV, 2012).

Motivational models describe how road users adapt their behaviour to the environment if the driving task is self-paced (Ranney, 1994). Homeostasis models assume that drivers are constantly aware of, monitor and seek to maintain a set level or range of a variable, such as risk (e.g. Wilde's risk homeostasis model; Wilde, 1982) or task difficulty (e.g. Fuller's task-difficulty homeostasis model; Fuller, 2005). A second group of theories claims that variables such as a perception or feeling of risk are only experienced at certain times during driving, i.e. when a certain threshold is exceeded (Lewis-Evans et al., 2011), for instance the Zero-Risk theory developed by Näätänen and Summala (1974). A problem with these motivational theories is that they do not describe to what extent road users may adapt their behaviour in response to certain measures. Bjørnskau (1994) proposed hypotheses designed to explain road user behavioural adaptation to road safety measures. For instance, highly visible changes to the road are more likely to lead to behavioural adaptation than measures that road users do not easily notice. Visible measures such as blue-painted bicycle crossings have been shown to result in behavioural adaptation. Fewer cyclists turned their heads to scan for traffic or used hand signals after the measure was implemented (Hunter et al., 2000). Note that Section 3.2.3 describes the risk perceived and its effect on decisions taken *before* traffic participation, whereas this section described the perception of risk and its effect on behaviour *during* traffic participation.

3.3.2. *Physical factors*

In the context of this paper, the term 'physical factors' is used to refer to the interaction between vehicles and road infrastructure. An example is the friction between tires and the road surface needed for braking. Nyberg et al. (1996) have shown that a slippery road surface contributes to single-bicycle crashes. They therefore advise investment in winter maintenance. The remainder of this section focuses on bicycle stability because it may play an important role in single-bicycle crashes.

A controlling rider can balance a forward-moving bicycle by turning the front wheel in the direction of an undesired lean, i.e. steering to the right when falling to the right, and vice versa. This moves the ground-contact points under the rider and results in a zig-zag movement. Most bicycles can balance themselves ('riderless') if moving above a given speed, because they are able to steer into the lean automatically. Godthelp and Wouters (1978) used an experiment to estimate that under normal circumstances and speeds, cyclists require a track width of about 1 metre to accommodate the resulting zig-zag movement and space for the bicycle. They recommend a minimum width of 2 m for one-way bicycle tracks to enable cyclists to overtake safety.

Moore et al. (2009) found self-stability at speeds above approximately 15 km/h for a commonly used Dutch city bicycle and a male rider. Stabilizing a bicycle at low speed requires more active steering. Several factors, including geometry, mass distribution and gyroscopic effect all contribute in varying degrees to this self-stability. Long-standing hypotheses and claims that any single effect, such as gyroscopic or trail, is solely responsible for the stabilizing force have been discredited (Kooijman et al., 2011). The role of speed in stability suggests that the design of bicycle facilities should enable cyclists to maintain a minimum speed, e.g. sufficiently large curve radii and not too steep a slope (see e.g. CROW, 2007).

The stability also depends on the freedom of the front fork to swivel. If it is locked, such as when the front wheel becomes stuck in the tram rails, the bicycle cannot be ridden. A difference in height between the road surface and shoulder surface makes it difficult for the cyclist to steer back after riding off the road, and can lead to falls (Schepers and Klein Wolt, 2012). Finally, it is obvious that road surface irregularities such as potholes contribute to loss of control and thereby single-bicycle crashes (Nyberg et al., 1996). Dutch design guidelines advise that bicycle crossings intersect tram rails perpendicularly, the difference between the level of the road and shoulder surface be minimal, and the road surface be well maintained, etc. (CROW, 2007; Van Boggelen et al., 2011).

3.4. Injury risk

This section explains injury risk for cyclists and how it is affected by infrastructure characteristics. The amount of kinetic energy produced is a function of the mass and velocity (speed): $1/2\,mv^2$ (m = mass; v = speed). The law of conservation of energy states that the total amount of energy in an isolated system is conserved over time. In road crashes, kinetic energy is partly conserved and partly converted to other types of energy such as deformation energy and heat. Part of the kinetic energy is transferred to the victims involved in the crash. Crashes may be fatal when these forces exceed the victims' biomechanical tolerance (Corben et al., 2004). Crumple zones, air bags, and crash barriers slow the stopping process and spread the crash energy of the crash out over time, reducing the peak spike of energy to the human body. Similarly, airbags on the windscreen (Rodarius et al., 2008) or bicycle helmets (Elvik, 2011) may protect cyclists in the event of a crash. This principle is called 'physical forgivingness' in the case of road side furniture (Wegman et al., 2012). The principle has to our best knowledge not yet been applied to the design of for instance obstacles with which cyclists may collide.

When different categories of vehicles or road users crash, their compatibility in terms of mass and speed influences the accident outcome. Compatibility refers to the differences between categories of road users in terms of the kinetic energy produced by their movements. The smaller these differences, the more compatible are road users.

Elvik (2010) calculated for each transport mode, the ratio of the number of casualties among those in other modes of transport divided by the number of casualties in the vehicle type under question. For instance, the ratio for transport mode x would be 0.5 if 500 road users were injured in other modes versus 1000 in mode x. The ratio ranged from 0.03 for pedestrians and 0.05 for cyclists to 0.27 for car occupants and 3.46 for truck occupants. The problem of incompatibility contributed to the development of the Sustainable Safety principle of 'homogeneity'. This states that where road users or vehicles with large mass differences use the same traffic space, the speeds should be so low that the most vulnerable road users and transport modes come out of a crash without any severe injuries (Wegman et al., 2012).

The idea that the most severe injuries can be prevented by keeping speeds under a threshold for certain combinations of road users led to the concept of 'safe speeds'. Tingvall and Haworth (1999) consider 30 km/h a safe speed where vulnerable road users are mixed with motorized vehicles. Several studies have confirmed that there is a threshold around 30 km/h, above which the probability of injury and fatality for pedestrians and cyclists colliding with motor vehicles strongly increases (Kim et al., 2007; Rosén et al., 2011). However, this does not apply to lorries, where far lower speeds can easily end in a fatality if a cyclist goes under the wheels (Schoon, 2006).

4. Example of application of the framework: converting one-way into two-way bicycle tracks

The measure of converting one-way into two-way cycle tracks in an urban area is described to exemplify the framework's application to cycling safety. The measure is considered by a municipality that wants to increase the amount of cycling and improve cycling safety.

We firstly address potential effects on exposure. Cyclists have right of way while travelling along distributors. Two-way cycle tracks make a route along such roads even more attractive. Cyclists do not have to cross the road to travel at the right-hand side (in the case of right-hand driving). The reduced stopping frequency may, to a small extent, increase the amount of cycling (Rietveld and Daniel, 2004) and may affect route choice to the extent that the route along the distributor reduces travel time (Gommers and Bovy, 1987). More cyclists travelling along distributors instead of through traffic-calmed areas affects the exposure of cyclists to high-speed motorists. Through motor traffic is kept out of traffic-calmed areas, resulting in a reduced exposure on access roads. Most bicycle–motor vehicle crashes at distributor roads are collisions between through cyclists and motorists from the side road (Schepers et al., 2011). Secondly, we address the relationship between exposure and risk. The slightly increased amount of cycling and higher proportion of cycling in the modal split can be expected to have hardly any effect on the number of fatalities, although it would increase the number of seriously injured casualties (Stipdonk and Reurings, 2012; Schepers and Heinen, 2013). Lastly, we describe potential effects on risk due to two-way instead of one-way bicycle tracks. Two-way cycle tracks increase crash risks because cyclists at the left side of the road come from an unexpected direction for drivers from the minor road (Summala et al., 1996; Schepers et al., 2011).

The results of the analysis suggest that converting one-way bicycle tracks into two-way may slightly increase bicycle usage and increase the number of bicycle–motor vehicle crashes. Although the framework does not allow for quantitative assessment, the example shows its value for identifying potential effects. The effect on crashes due to a changed distribution of cyclists over the road network is normally not addressed in road safety research. For instance, the study by Schepers et al. (2011) is one of the few which controlled for volumes of both motorists and cyclists to determine the effect of two-way versus one-way bicycle tracks at unsignalized priority intersections on the risk of bicycle–motor vehicle crashes. To the best of our knowledge, there is no study that includes the potential adverse effects of more cyclists choosing routes along distributor roads where cyclists are exposed to a higher risk of bicycle–motor vehicle crashes.

5. Discussion

This paper presented a conceptual road safety framework comprising factors determining exposure to risk (resulting from travel behaviour), risk (injury and crash risk), and the relationship between these two. Models for travel behaviour and road safety are not new, but to the best of our knowledge, nowhere in the scientific literature is there a framework comprising both and the relationship between them. The framework can be used to acquire insight into the potential effects of measures. An example of such an effect (identified in Section 4) is a changed distribution of traffic over the road network resulting from conversion of one-way bicycle tracks to two-way. We believe that this effect, which is important for exposure of cyclists to high-speed motorists, has not yet been addressed in any study on road factors and bicycle crashes. The framework as described in this paper can help to identify such potential effects.

5.1. *Research recommendations regarding the framework*

Future research may require the framework to be broadened or adapted for application to subjects other than cycling. A first additional application could be the post-crash phase in which, for instance, the emergency medical system is relevant. For application to pedestrian safety, where it would be useful to be able to describe falls in which no vehicles are involved, it may be helpful to replace 'road users, vehicles, and infrastructure' by Haddon's (1980) 'host (the pedestrian), agent (kinetic energy and gravity), and environment (the road and social environment)'. Secondly, the model is conceptual and does not allow for quantitative assessment of the effects on (injury) crash numbers. Empirical studies would be needed for this. However, it would be possible to test the model against the findings of a broader literature search on cycling safety. We recommend a literature review to explore the effects of a broad range of measures on bicycle usage and cycling safety included by governments in bicycle plans. The outcomes may reveal elements or links missing in the model.

In the interests of maintaining ease of communication, we advise against expanding the number of elements in the framework too much. Instead we recommend to seek models that are more specific to explain relationships in the model in more detail. This might be more complicated than it seems. For instance, in the case of the link between road users and infrastructure, no theory of driver behaviour has yet managed to achieve widespread acceptance (Lewis-Evans et al., 2011), human factors theories are developed mainly from the perspective of the individual road user, which hampers relating them to design features. While design principles such as 'geometric consistency' can be accommodated in human factors theories, most are not embedded in models which could show their relationship to other concepts. A review of models for relations in our framework could be of help for researchers designing new studies.

5.2. *Research gaps regarding cycling safety, land use and infrastructure*

The subject of cycling safety, land use and infrastructure was used in this paper to exemplify application of the framework. The literature survey conducted for this purpose has shown a number of research gaps of which we give some examples in the areas of travel behaviour, the relationship between exposure and risk, and risk. We firstly address travel behaviour.

5.2.1. *Travel behaviour*

Heinen et al. (2010) indicate that large mode choice studies often lack factors relating specifically to bicycle use. Many bicycle research studies examine only a limited number of factors, which make it difficult to determine their relative importance. Little or no research focused on the effect of certain aspects of infrastructure, such as bicycle tracks, the presence of traffic lights, and pavement quality (Heinen et al., 2010). At the network level, there is the question of whether providing more direct routing for cyclists rather than for motorists would increase the share of cycling in the modal split (Frank and Hawkins, 2008). An important safety consideration is how a road hierarchy with bicycle-specific measures such as bicycle bridges and tunnels may decrease cyclist exposure to high-speed motorists at distributors and thereby improve cycling safety. To the best of our knowledge this has not yet been studied.

5.2.2. *The relationship between exposure (resulting from travel behaviour) and risk*

Research on this issue resulted in Accident Prediction Models that help estimate the effect of a modal shift on road safety (e.g. Elvik, 2009; Schepers and Heinen, 2013). Researchers have suggested several possible explanations for the non-linear relationship between traffic volumes and risk but the internal validity of current studies was not strong enough for inferring causality (Bhatia and Wier, 2011). A better understanding is important for policy makers, e.g. policy could focus on infrastructure if the non-linearity results from improved infrastructure (Bhatia and Wier, 2011; Wegman et al., 2012). A similar lack of internal validity seems to apply to research on the effect of perceived risk on bicycle use. Not only is reduced perceived risk associated with increased bicycle usage, it also tends to alter the compilation of the cyclist population because some groups, such as women and the elderly, appear to be especially sensitive to road safety (Pucher and Buehler, 2008; Heinen et al., 2010). These particular groups of cyclists may have a different risk profile which could change cyclist crash rates. The fact of these groups taking up cycling may change how people perceive the risk of cycling, and so on. Exploration of the causal mechanisms that might explain the relationship between risk and bicycle usage is challenge for future research, and could help substantiate the links in between the upper and lower part of our model.

5.2.3. *Risk*

Reynolds et al. (2009) conclude from their review study that there is good research on the effect of the provision of bicycle facilities on road sections and roundabouts on cycling safety, but less on signalized and unsignalized intersections. Furthermore, many researchers focus on the presence of a facility, but pay little attention to how it is designed (Reynolds et al., 2009), indicating that many studies are not yet well underpinned by human factors theories (Schepers et al., 2011). While much research has focused on the risk of bicycle–motor vehicle crashes, only a few studies focused on single-bicycle crashes (Schepers and Klein Wolt, 2012). A small number of studies indicated that aspects such as winter maintenance of bicycle facilities, road surface quality and the visual design of infrastructure play a role in single-bicycle crashes (Nyberg et al., 1996; Schepers and Den Brinker, 2011). However, evaluation studies on the effects of infrastructure on single-bicycle crashes are not yet available. These research gaps show that our theoretical understanding of how infrastructure is related to road users and vehicles can be improved.

Finally, it is worth mentioning that even when cycling safety research is available, one needs to take into account that, because of the considerable differences between countries in cycling and cycling safety conditions, the outcomes cannot easily be generalized (Loo and Tsui, 2010; Wegman et al., 2012). Our understanding can be further improved by conducting similar type of studies in different countries.

5.3. *Relevance for transport policy*

From a policy perspective, a broad framework comprising both travel behaviour and risk factors is important because governments often have goals for both. For instance, they generally aim to improve road safety and increase the amount of cycling at the same time. Wegman et al. (2012) therefore posed the question of how to consider increased cycling and better cycling safety simultaneously. Effects of changed amounts of cycling (and walking) such as those resulting from changes in cyclists' travel time, road users' perception of safety, and health are often ignored in current cost–benefit analyses of measures designed to improve safety or mobility for pedestrians and cyclists (Elvik, 2000; Van Wee et al., in press).

Influential road safety visions such as Vision Zero (Tingvall and Haworth, 1999), Sustainable Safety (Wegman and Aarts, 2006), and Safe Systems (ACT, 2008) are critical to road safety improvement. However, they are not developed to provide insight into the effects of policies on travel behaviour. A framework such as the one outlined in this paper is a starting point for acquiring insight into both travel behaviour and safety effects, and exploring whether some measures may be conflicting.

References

ACT, 2008. National Road Safety Action Plan 2009 and 2010. Australian Transport Council, Canberra.

Ajzen, I., 1985. From intentions to actions: a theory of planned behavior. In: Kuhl, J., Beckmann, J. (Eds.), Action Control: From Cognition to Behavior. Springer-Verlag, New York.

Aram, A., 2010. Effective safety factors on horizontal curves of two-lane highways. Journal of Applied Sciences 10, 2814–2822.

Ardekani, S., Hauer, E., Jamei, B., 2000. Traffic impact models. In: Gartner, N., Messer, C.J., Rathi, A.K. (Eds.), Traffic Flow Theory: A State of the Art Report. Federal Highway Administration, Washinton.

Asmussen, E., Kranenburg, A., 1982. An Analysis of the Traffic Phenomenon. Institute for Road Safety Research, Leidschendam.

Barnes, G.R., Thompson, K.B., 2006. A longitudinal analysis of the effect of bicycle facilities on commute mode share. In: Transportation Research Board 85th Annual Meeting, Transportation Research Board, Washington, DC.

Berends, E.M., Stipdonk, H.L., 2009. De veiligheid van voetgangers en fietsers op 30 km/uur-erftoegangswegen (Pedestrian and Cyclist Safety on 30 km/h Access Roads). Institute for Road Safety Research, Leidschendam.

Bhatia, R., Wier, M., 2011. "Safety in numbers" re-examined: can we make valid or practical inferences from available evidence? Accident Analysis and Prevention 43 (1), 235–240.

Birth, S., Pflaumbaum, M., Potzel, D., Sieber, G., 2009. Human Factors Guideline for Safer Road Infrastructure. World Road Association, Paris.

Bjørnskau, T., 1994. Hypotheses on risk compensation. In: Proceedings of the Conference Road Safety in Europe, Strategic Highway Research Program (SHRP), Lille, France, pp. 81–98.

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

Brüde, U., Larsson, J., 2000. What roundabout design provides the highest possible safety? Nordic Road and Transport Research 12 (2), 17–21.

Buchanan, C., 1963. Traffic in Towns. Her Majesty's Stationery Office, London.

Chorus, C.G., Arentze, T.A., Timmermans, H.J.P., 2008. A random regret-minimization model of travel choice. Transportation Research Part B: Methodological 42 (1), 1–18.

Corben, B., Senserrick, T., Cameron, M., Rechnitzer, G., 2004. Development of the Visionary Research Model. Monash University Research Centre, Clayton.

CROW, 2007. Design Manual for Bicycle Traffic. CROW, Ede.

Daniels, S., Brijs, T., Nuyts, E., Wets, G., 2009. Injury crashes with bicyclists at roundabouts: influence of some location characteristics and the design of cycle facilities. Journal of Safety Research 40 (2), 141–148.

Davidse, R., 2007. Assisting the Older Driver: Intersection Design and In-car Devices to Improve the Safety of the Older Driver. Institute for Road Safety Research, Leidschendam.

De Hartog, J.J., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Environmental Health Perspective 118 (8), 1109–1116.

De Waard, D., 1996. The Measurement of Drivers' Mental Workload. Groningen University, Groningen.

De Waard, D., Schepers, J.P., Ormel, W., Brookhuis, K.A., 2010. Mobile phone use while cycling: incidence and effects on behaviour and safety. Ergonomics 53, 30–42.

Dijkstra, A., 2004. Rotondes met vrijliggende fietspaden ook veilig voor fietsers? (Are Roundabouts with Separate Cycle Tracks also Safe for Cyclists?). Institute for Road Safety Research, Leidschendam.

Donges, E., 1978. A two-level model of driver steering behavior. Human Factors 20 (6), 691–707.

Elvik, R., 2000. Which are the relevant costs and benefits of road safety measures designed for pedestrians and cyclists? Accident Analysis and Prevention 32 (1), 37–45.

Elvik, R., 2004. To what extent can theory account for the findings of road safety evaluation studies? Accident Analysis and Prevention 36 (5), 841–849.

Elvik, R., 2006. Laws of accident causation. Accident Analysis and Prevention 38 (4), 742–747.

Elvik, R., 2009. The non-linearity of risk and the promotion of environmentally sustainable transport. Accident Analysis and Prevention 41 (4), 849–855.

Elvik, R., 2010. Why some road safety problems are more difficult to solve than others. Accident Analysis and Prevention 42 (4), 1089–1096.

Elvik, R., 2011. Publication bias and time-trend bias in meta-analysis of bicycle helmet efficacy: a re-analysis of attewell, glase and McFadden, 2001. Accident Analysis and Prevention 43 (3), 1245–1251.

Elvik, R., Bjørnskau, T., 2005. How accurately does the public perceive differences in transport risks? An exploratory analysis of scales representing perceived risk. Accident Analysis and Prevention 37 (6), 1005–1011.

Elvik, R., Vaa, T., 2009. The Handbook of Road Safety Measures. Elsevier, Oxford.

EuroNCAP, 2012. European New Car Assessment Programme, Retrieved from: http://www.euroncap.com/ (28.10.12).

EuroRap, 2011. European Road Assessment Programme, Retrieved from: http://www.eurorap.org/ (28.10.12).

Fitzpatrick, K., Wooldridge, M.D., Tsimhoni, O., Collins, J.M., Green, P., Bauer, K., Parma, K.D., Harwood, R.K., Krammes, D.W., Poggioli, R.B., 1999. Alternative Design Consistency Rating Methods for Two-Lane Rural Highways; fhwa-rd-99-172. FHWA, Washington, DC.

Ford, A., 2009. Modeling the Environment. Island Press, Washington, DC.

Frank, L., Hawkins, C., 2008. Assessing Travel and Environmental Impacts of Contrasting Levels of Vehicular and Pedestrian Connectivity: Assessing Aspects of the Fused Grid. Canada Mortgage and Housing Corporation, Ottawa.

Fuller, R., 2005. Towards a general theory of driver behaviour. Accident Analysis and Prevention 37 (3), 461–472.

Gårder, P., Leden, L., Pulkkinen, U., 1998. Measuring the safety effect of raised bicycle crossings using a new research methodology. Transportation Research Record 1636, 64–70.

Gibson, J.J., 1961. The contribution of experimental psychology to the formulation of the problem of safety. In: Jacobs, H.H. (Ed.), Behavioural Approaches to Accident Research. Association for the Aid of Crippled Children, New York.

Godthelp, H., Wouters, P.I.J., 1978. Koershouden voor fietsers en bromfietsers (Tracking ans Steering Control in Cyclists and Mopedists). Verkeerskunde 11, 537–543.

Goldenbeld, C., 1992. Ongevallen van oudere fietsers in 1991 (Crashes with Older Cyclists). Institute for Road Safety Research, Leidschendam.

Gommers, M.J.P.F., Bovy, P.H.L., 1987. Routekeuzegedrag en netwerkgebruik (Route Choice and Network Use). Delft University of Technology, Delft.

Haddon Jr., W., 1980. Advances in the epidemiology of injuries as a basis for public policy. Public Health Reports 95 (5), 411–421.

Hägerstrand, T., 1970. What about people in regional science? Papers in Regional Science 24, 6–21.

Hakkert, A.S., Braimaister, L., 2002. The Uses of Exposure and Risk in Road Safety Studies. Institute for Road Safety Research, Leidschendam.

Hatakka, M., Keskinen, E., Gregersen, N., Glad, A., 1999. Theories and aims of educational and training measures. In: Siegrist, S. (Ed.), Driver Training, Testing and Licencing. Swiss Counsil for Accident Prevention, Bern.

Heemskerk, M., Wilson, K., Pavao-Zuckerman, M., 2003. Conceptual models as tools for communication across disciplines. Conservation Ecology 7 (3), 8.

Heinen, E., Handy, S., 2012. Similarities in attitudes and norms and the effect on bicycle commuting: evidence from the bicycle cities davis and delft. International Journal of Sustainable Transportation 6 (5), 257–281.

Heinen, E., Maat, K., Van Wee, B., 2011. Day-to-day choice to commute or not by bicycle. Transportation Research Record 2230, 9–18.

Heinen, E., Van Wee, B., Maat, K., 2010. Commuting by bicycle: an overview of the literature. Transport Reviews 30 (1), 59–96.

Heinrich, H.W., 1931. Industrial Accident Prevention: A Scientific Approach. McGraw-Hill, New York.

Houtenbos, M., 2008. Expecting the Unexpected: A Study of Interactive Driving Behaviour at Intersections. Institute for Road Safety Research, Leidschendam.

Hummel, T., 2001. Route Management in Safer Transportation Network Planning.

Hunter, W.W., Harkey, D.L., Stewart, J.R., Birk, M.L., 2000. Evaluation of blue bike-lane treatment in Portland, Oregon. Transportation Research Record 1705, 107–115.

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

Janke, M.K., 1991. Accidents, mileage, and the exaggeration of risk. Accident Analysis and Prevention 23, 183–188.

Jensen, S.U., 1999. Pedestrian safety in Denmark. Transportation Research Record 1674, 61–69.

Kahneman, D., Tversky, A., 1979. Prospect theory: an analysis of decision under risk. Econometrica 47 (2), 263–291.

Kim, J.K., Kim, S., Ulfarsson, G.F., Porrello, L.A., 2007. Bicyclist injury severities in bicycle–motor vehicle accidents. Accident Analysis and Prevention 39 (2), 238–251.

Kooijman, J.D., Meijaard, J.P., Papadopoulos, J.M., Ruina, A., Schwab, A.L., 2011. A bicycle can be self-stable without gyroscopic or caster effects. Science 332 (6027), 339–342.

Leibowitz, H.W., Owens, D.A., 1977. Nighttime driving accidents and selective visual degradation. Science 197 (4302), 422–423.

Leibowitz, H.W., Post, R.B., 1982. The two modes of processing concept and some implications. In: Beck, J. (Ed.), Organization and Representation in Perception. Lawrence Erlbaum, Hillsdale, pp. 343–363.

Leveson, N., 2004. A new accident model for engineering safer systems. Safety Science 42 (4), 237–270.

Lewis-Evans, B., De Waard, D., Brookhuis, K.A., 2011. Speed maintenance under cognitive load – implications for theories of driver behaviour. Accident Analysis and Prevention 43 (4), 1497–1507.

Lie, A., Tingvall, C., 2002. How do euro ncap results correlate with real-life injury risks? A paired comparison study of car-to-car crashes. Traffic Injury Prevention 3 (4), 288–293.

Loo, B.P.Y., Tsui, K.L., 2010. Bicycle crash casualties in a highly motorized city. Accident Analysis and Prevention 42 (6), 1902–1907.

McFadden, D., 1974. Conditional logit analysis of qualitative choice-behaviour. In: Zarembka, P. (Ed.), Frontiers in Econometrics. Academic Press, New York, NY, pp. 105–142.

Michon, J.A., 1985. A critical view of driver behavior models. What do we know, what should we do? In: Evans, L., Schwing, R.C. (Eds.), Human Behavior and Traffic Safety. Plenum Press, New York.

Mokhtarian, P.L., Chen, C., 2004. Ttb or not ttb, that is the question: a review and analysis of the empirical literature on travel time (and money) budgets. Transportation Research Part A: Policy and Practice 38 (9–10), 643–675.

Moore, J.K., Hubbard, M., Kooijman, J.D.G., Schwab, A.L., 2009. A method for estimating physical properties of a combined bicycle and rider. In: Proceedings of the ASME Conference, San Diego, CA.

Moudon, A.V., Lee, C., Cheadle, A.D., Collier, C.W., Johnson, D., Schmid, T.L., Weather, R.D., 2005. Cycling and the built environment, a us perspective. Transportation Research Part D: Transport and Environment 10 (3), 245–261.

Näätänen, R., Summala, H., 1974. A model for the role of motivational factors in drivers' decision-making. Accident Analysis and Prevention 6 (3–4), 243–261.

Nyberg, P., Bjornstig, U., Bygren, L.O., 1996. Road characteristics and bicycle accidents. Scandinavian Journal of Social Medicine 24 (4), 293–301.

Oja, P., Titze, S., Bauman, A., De Geus, B., Krenn, P., Reger-Nash, B., Kohlberger, T., 2011. Health benefits of cycling: a systematic review. Scandinavian Journal of Medicine & Science in Sports 21 (4), 496–509.

Ormel, W., Klein Wolt, K., Den Hertog, P., 2008. Enkelvoudige fietsongevallen (Single-Bicycle Crashes). Stichting Consument en Veiligheid, Amsterdam.

Othman, S., Thomson, R., Lanner, G., 2009. Identifying critical road geometry parameters affecting crash rate and crash type. Annals of Advances in Automotive Medicine 53, 155–165.

Parkin, J., Wardman, M., Page, M., 2007. Models of perceived cycling risk and route acceptability. Accident Analysis and Prevention 39 (2), 364–371.

Previc, F.H., 1998. The neuropsychology of 3-d space. Psychological Bulletin 124 (2), 123–164.

Pucher, J., Buehler, R., 2008. Making cycling irresistible: lessons from the Netherlands, Denmark and Germany. Transport Reviews 28 (4), 495–528.

Ranney, T.A., 1994. Models of driving behavior: a review of their evolution. Accident Analysis and Prevention 26 (6), 733–750.

Räsänen, M., Summala, H., 1998. Attention and expectation problems in bicycle–car collisions: an in-depth study. Accident Analysis and Prevention 30 (5), 657–666.

Reurings, M.C.B., 2010. Hoe gevaarlijk is fietsen in het donker? (How Dangerous is Cycling in Darness?). Institute for Road Safety Research, Leidschendam.

Reynolds, C.C., Harris, M.A., Teschke, K., Cripton, P.A., Winters, M., 2009. The impact of transportation infrastructure on bicycling injuries and crashes: a review of the literature. Environmental Health 8, 47.

Rietveld, P., Daniel, V., 2004. Determinants of bicycle use: do municipal policies matter? Transportation Research Part A: Policy and Practice 38 (7), 531–550.

Rodarius, C., Mordaka, J., Versmissen, T., 2008. Bicycle Safety in Bicycle to Car Accidents. TNO Science and Industry, Delft.

Rosén, E., Stigson, H., Sander, U., 2011. Literature review of pedestrian fatality risk as a function of car impact speed. Accident Analysis and Prevention 43 (1), 25–33.

Rumar, K., 1999. Transport Safety Visions, Targets and Strategies: Beyond 2000. European Transport Safety Council, Brussels.

Sakshaug, L., Laureshyn, A., Svensson, Å., Hydén, C., 2010. Cyclists in roundabouts—different design solutions. Accident Analysis and Prevention 42 (4), 1338–1351.

Schepers, J.P., 2012. Does more cycling also reduce the risk of single-bicycle crashes? Injury Prevention 18 (4), 240–245.

Schepers, J.P., Den Brinker, B.P.L.M., 2011. What do cyclists need to see to avoid single-bicycle crashes? Ergonomics 54 (4), 315–327.

Schepers, J.P., Heinen, E., 2013. How does a modal shift from short car trips to cycling affect road safety? Accident Analysis and Prevention 50 (1), 1118–1127.

Schepers, J.P., Klein Wolt, K., 2012. Single-bicycle crash types and characteristics. Cycling Research International 2, 119–135.

Schepers, J.P., Kroeze, P.A., Sweers, W., Wust, J.C., 2011. Road factors and bicycle–motor vehicle crashes at unsignalized priority intersections. Accident Analysis and Prevention 43 (3), 853–861.

Schieber, F., Schlorholtz, B., Mccall, R., 2008. Visual requirements of vehicular guidance. In: Castro, C. (Ed.), Human Factors of Visual and Cognitive Performance in Driving. CRC Press, Boca Raton.

Schoon, C.C., 2006. De problematiek van rechtsafstaande vrachtauto's (The Problem of Lorries Turning Right). Institute for Road Safety Research, Leidschendam.

Sobhani, A., Young, W., Logan, D., Bahrololoom, S., 2011. A kinetic energy model of two-vehicle crash injury severity. Accident Analysis and Prevention 43 (3), 741–754.

Southworth, M., 2005. Designing the walkable city. Journal of Urban Planning and Development 131 (4), 246–257.

Stipdonk, H., Reurings, M., 2012. The effect on road safety of a modal shift from car to bicycle. Traffic Injury Prevention 13 (4), 412–421.

Summala, H., Pasanen, E., Räsänen, M., Sievänen, J., 1996. Bicycle accidents and drivers' visual search at left and right turns. Accident Analysis and Prevention 28 (2), 147–153.

SWOV, 2012. Factsheet Attention Problems Behind the Wheel. Institute for Road Safety Research, Leidschendam.

Theeuwes, J., Godthelp, H., 1995. Self-explaining roads. Safety Science 19 (2–3), 217–225.

Theeuwes, J., Hagenzieker, M.P., 1993. Visual search of traffic scenes: on the effect of location expectations. In: Gale, A.G., Freeman, M.H., Haslegrave, C.M., Smith, P., Taylor, S.P. (Eds.), Vision in Vehicle IV. Elsevier Science, Amsterdam.

Tingvall, C., Haworth, N., 1999. Vision zero – an ethical approach to safety and mobility. In: 6th ITE International Conference Road Safety & Traffic Enforcement: Beyond 2000, Melbourne.

Toft, Y., Dell, G., Klockner, K.K., Hutton, A., 2012. Models of Causation: Safety. Safety Institute of Australia, Tullamarine, Victoria.

Van Boggelen, O., Schepers, J.P., Kroeze, P.A., Van Der Voet, M., 2011. Fietsberaad-publicatie 19: Samen werken aan een veilige fietsomgeving (Collaborating to Improve Cycling Safety). Fietsberaad, Utrecht.

Van de Kaa, E.J., 2010. Prospect theory and choice behaviour strategies: review and synthesis of concepts from social and transport sciences. European Journal of Transport and Infrastructure Research 10 (4), 299–329.

Van Wee, B., 2009. Verkeer en transport. In: Van Wee, B., Anne Annema, J. (Eds.), Verkeer en vervoer in hoofdlijnen (Outlining Traffic and Transport). Coutinho, Bussum.

Van Wee, B., Maat, K., 2003. Land-use and transport: a review and discussion of dutch research. European Journal of Transport and Infrastructure Research 3 (2), 199–218.

Van Wee, B., Rietveld, P., Meurs, H., 2006. Is average daily travel time expenditure constant? In search of explanations for an increase in average travel time. Journal of Transport Geography 14 (2), 109–122.

Van Wee, G.P., Hagenzieker, M.P., Wijnen, W. Which indicators to include in the ex ante evaluations of the safety effects of policy options? Gaps in evaluation and a discussion based on an ethical perspective. Transport Policy, in press.

Vandenbulcke-Plasschaert, G., 2011. Spatial Analysis of Bicycle Use and Accident Risks for Cyclists. Université catholique de Louvain, Louvain.

Viner, D., 1991. Accident Analysis and Risk Control. Derek Viner Ltd., Melbourne.

Vlakveld, W.P., 2005. Jonge beginnende automobilisten, hun ongevalsrisico en maatregelen om dit terug te dringen (Young Novice Drivers, their Crash Risk and Preventive Measures). Institute for Road Safety Research, Leidschendam.

Vlakveld, W.P., Goldenbeld, C., Twisk, D.A.M., 2008. Beleving van verkeersonveiligheid (Perception of Lack of Traffic Safety). Institute for Road Safety Research, Leidschendam.

Vlakveld, W.P., Louwerse, W.J.R., 2011. De relatie tussen road protection scores (rps) en het slachtofferrisico op wegvakken van provinciale wegen in utrecht (The Relation Between Road Protection Scores (rps) and the Casualty Rate at Road Sections in the Province of Utrecht). Institute for Road Safety Research, Leidschendam.

Vlek, C., Jager, W., Steg, L., 1997. Modellen en strategieën voor gedragsverandering ter vermindering van collectieve risico's (Models and Strategies for Behavioural Change in Order to Reduce Collective Risks). Nederlands tijdschrift voor de Psychologie 52, 174–191.

Wegman, F.C.M., Aarts, L.T., 2006. Advancing Sustainable Safety: National Road Safety Outlook for 2005–2020. Institute for Road Safety Research, Leidschendam.

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

Weller, G., Schlag, B., 2007. Driver Behaviour Model: Ripcord-Inserest Deliverable d8. Technische Universität Dresden, Dresden.

Wilde, G.J.S., 1982. The theory of risk homeostasis: implications for safety and health. Risk Analysis 2 (4), 209–225.

Zacharias, J., 2005. Non-motorized transportation in four shanghai districts. International Planning Studies 10 (3–4), 323–340.