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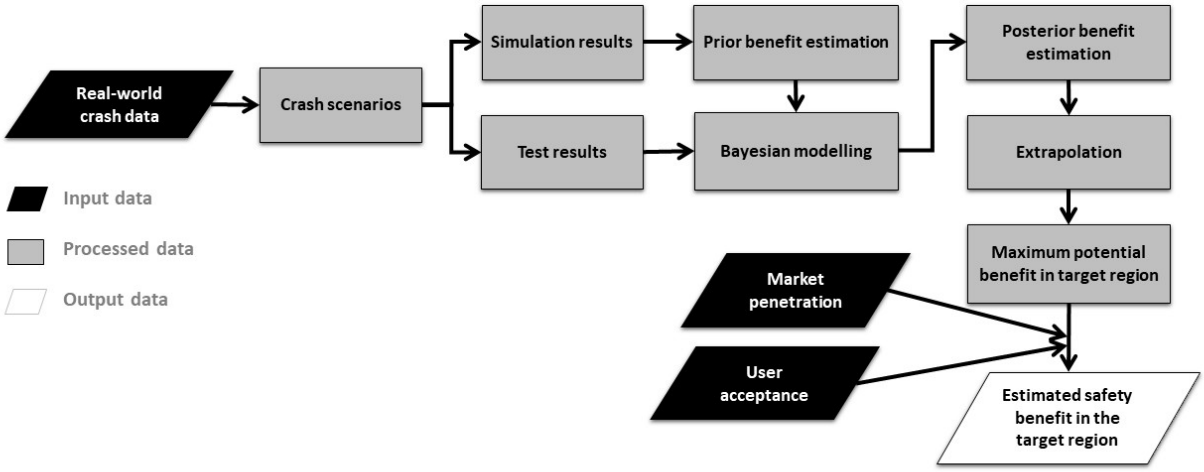

Towards an Improved Safety Benefit Assessment for Heavy Trucks

Introduction of a framework for the combination of different data sources

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Department of Mechanics and Maritime Sciences
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Göteborg, Sweden 2020

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN MACHINE AND VEHICLE SYSTEMS

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Cover:
Visualisation of the safety benefit assessment framework

Chalmers Reproservice
Göteborg, Sweden 2020

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Abstract

Although heavy goods vehicles (HGVs) were only involved in 4.4% out of more than 1 million crashes that occurred on European roads in 2017, their share in crashes with fatal outcome was almost three times larger (12%). Advanced Driver Assistance Systems (ADAS) have the potential to mitigate the consequences of these crashes or avoid them altogether. In order to prioritise the most promising system, several types of safety benefit assessment are performed separately and independently of each other. These assessments miss however a combination into a common output, i.e. they are not able to provide a holistic overview but only show compartmentalised results.

The first objective of this thesis is to provide a framework that can incorporate multiple data sources and combine their results into one common safety benefit output. The proposed framework within this thesis is based on Bayesian modelling and can update prior information (e.g. simulation results of a new ADAS) with new observations (e.g. test track results of the ADAS). The framework can incorporate additional information such as user acceptance and market penetration of the ADAS for an improved benefit assessment. The output of the framework can easily be incorporated as prior knowledge in new safety benefit assessments, e.g. when new data is available.

The second objective is to prepare the application of the framework for the assessment of the safety benefit associated to the introduction of new ADAS for long-haul trucks. In order to specify the most critical crash scenarios for HGVs in Europe, a detailed, three-level analysis of crashes involving long-haul trucks was performed, starting on a general European level and going to in-depth crash data. The identified target scenarios are (a) rear-end crashes with the truck as the striking vehicle, (b) crashes between a right-turning truck and adjacent cyclist and (c) crashes between a truck and a pedestrian crossing in front of the truck. These three scenarios should be the basis for ADAS development and further addressed by driver behaviour modelling in the future.

Future work will focus on improving simulation results by incorporating more accurate driver models, that are better able to represent truck driver behaviour, e.g. brake or steering reactions. These models will help to obtain more valid simulation results, and thereby increase the output quality of the framework.

Keywords: safety benefit assessment, Bayesian modelling, crash data analysis, CARE, GIDAS

Für Detlef
Für Wolfgang
Für meine Familie
Für meine Freunde
Für mich

ACKNOWLEDGEMENTS

I would like to thank my supervisors András and Giulio for their valuable support. Thanks for being there for me and supporting me with my stupid and clever questions as well my shorter and longer ones. I would like to thank my examiner Rob for his support as well as for reminding me of the bigger picture and how to reorganise my chaos. I would like to thank all my other colleagues at the division, that are still there or not, for the fun as well as feedback and support that kept me going forward. Especially thanks to Jason, Ellinor and Amanda for brightening up my days even when it's dark outside, before, during and after work.

I would like to thank my family and friends outside of work, who support me even when living further and further away. Thank you Beate for letting me go my way, even though that keeps me moving around. Thank you Franz, I am very grateful for your support during all these years, thanks for always being there for me.

Furthermore, I would like to thank the colleagues that I had the honour to work with in the several projects during the first two years of my PhD, namely in PROSPECT, AEROFLEX and TRUBADUR. I would also like to thank all the colleagues that supported me during my research visits, both to MHH and UMTRI. I would like to acknowledge that this PhD project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 769658.

Last but not least, I would like to thank all the reviewers (not only of this thesis, but also of the papers that are part of this thesis) for their feedback that helped to make this work better and stronger. Nevertheless, I claim total ownership of all mistakes that remain.

ABBREVIATIONS

16t+ truck	Heavy Goods Vehicles with a combination weight above 16t
ACAS	Accident Causation Analysis System
ADAS	Advanced Driver Assistance System
AEBS	Advanced Emergency Braking System
AEBSS	Autonomous Emergency Braking and Steering System
CARE	Community Database on Accidents on the Roads in Europe
FCW	Frontal Collision Warning
FOT	Field Operational Test
GIDAS	German In-Depth Accident Study
GIDAS-PCM	German In-Depth Accident Study - Pre Crash Matrix
HGV	Heavy Goods Vehicle (with a weight above 3.5t)
KSI	Killed or Severely Injured
STRADA	Swedish Traffic Accident Data Acquisition - Swedish national crash database
VRU	Vulnerable Road User

CONTENTS

1 Background

In 2017, more than 1 million crashes occurred on European roads. Although heavy goods vehicles (HGVs) were only involved in 4.4% of these crashes, their proportion in crashes with fatal outcome was almost three times larger (12%) (European Commission Directorate General for Mobility and Transport, 2019a). This over-representation of HGVs in fatal crashes calls for actions that can support the efforts to reach the vision of zero fatalities in Sweden (see Kristianssen et al., 2018) and the European Union (see European Commission Directorate General for Mobility and Transport, 2019b). To improve the crash safety towards other road users from a vehicle perspective, especially towards cyclists and pedestrians, the development and implementation of passive as well as active safety systems is necessary.

1.1 The role of active and passive safety systems

Passive safety systems have the goal to mitigate the injury outcome, once a crash has occurred. Seat belts and airbags have been used for a long time and have the goal to reduce the forces and accelerations on the occupants inside the vehicle during a crash (Viano, 1991). In recent years, the use of airbags has been extended to the outside of passenger vehicles, with the implementation of bonnet airbags that can protect pedestrians and cyclists (see Choi et al., 2014), but similar trends are missing for trucks. Due to the large mass difference and therefore high energy transfer, the crash outcomes in truck to vehicle crashes as well as truck to vulnerable road user (VRU) crashes are severe (Evgenikos et al., 2016), even at low speeds.

The current legislation in Europe (Directive (EU) 2015/719) sets a fixed combination length for trucks. Therefore, the implementation of larger crumple zones at the front of the truck - that could help to reduce the injury outcome - is problematic, as these crumple zones would decrease the loading volume of the vehicle. Although truck drivers generally sustain less severe injuries in crashes with cars or VRUs, especially when compared to the injuries of the crash opponents (see Malczyk and Koch, 2019), the implementation of active and passive safety systems is crucial to reduce the overall number of injuries.

Passive safety systems that would protect VRUs are reaching their limits in crashes with HGV involvement. Especially run-over crashes, where the truck rolls over the VRU, lead even at low speeds to severe injury outcomes (Strandroth, 2009) as the main injury mechanism is not so much related to the impact speed but rather to the weight of the truck. This injury mechanism makes it also nearly impossible to mitigate roll-over crashes with today's passive safety systems. An under-run protection might help avoid these crashes (and would likely also bring other benefits such as a decrease of the aerodynamic drag), but is yet to be implemented. In the above described situations, active safety systems seem promising (Strandroth, 2009). Their goal is to identify conflicts before they happen and by taking action, avoiding a collision altogether or reducing the severity of the collision, e.g. by reducing the impact speed. Especially active safety systems in the form of advanced driver assistance systems (ADAS) are becoming more and more relevant to achieve the goal of zero fatalities in road traffic. The importance of these systems is further increased as they are the basis for designing autonomous vehicles in the future. ADAS have to cover a wide range of target scenarios (e.g. navigating through an intersection, driving on the highway) and conditions (e.g. sunny or rainy weather, dry or icy roads), resulting in the following questions:

- How well does a specific ADAS work in a defined target scenario?
- Which ADAS design works best in multiple or all scenarios?
- How can different ADAS be tested with a reasonable amount of time and resources?

1.2 Safety benefit evaluation

In order to evaluate the proposed ADAS and improve their performance, a safety benefit assessment (i.e. an estimation of the change in injury outcome caused by the system) needs to be performed, so that development efforts can be focused on the most promising systems. Typical approaches for the safety benefit assessment are retrospective and prospective methods. Retrospective methods use crash databases (e.g. Persaud et al., 2001; Gårder and M. Davies, 2006 or Sternlund et al., 2017), insurance claims (e.g. Kuehn, Hummel, and Bende, 2009; Doyle, A. Edwards, and Avery, 2015; Isaksson-Hellman and Lindman, 2016; Cicchino, 2017 or Cicchino, 2018) or naturalistic driving data (e.g. Noort, Faber, and Bakri, 2012). These procedures aim to evaluate the effects of systems after their implementation and are therefore relatively slow, as the systems need time to be widespread in the market and show effects in real-world traffic. With the increasing pace of the development of new systems, approaches that aim to predict the system performance seem more promising.

Prospective assessments can be performed during the development process of the system, as soon as a model representing the new ADAS is available and before it is implemented into production models. Typical approaches are real-world testing and simulations. In real-world testing, as for example in M. Edwards et al. (2015), the actual systems can be tested and their real-world performance is evaluated either in a safe test track environment or on open roads, ensuring high validity of the recorded data. However, due to time and budget constraints, only a limited amount of tests can be performed, typically with dummies and robots replacing drivers (e.g. Euro NCAP testing).

Driving simulators, where human drivers are interacting with the systems in a virtual environment, are another possibility to test new systems. Simulators provide a safe experimental set-up (critical situations can be tested without subjecting the drivers to risk of bodily harm) and a high grade of experimental control (Nilsson, 1993; Alm and Nilsson, 1994; Bertollini et al., 1994 or Reed and Green, 1999). Very simple fixed-base simulators as well as advanced moving-base simulators, that can represent a more valid or ”realistic” situation, can be used (see Freeman, 1994 or Reed and Green, 1999). However, the ecological validity of the results (i.e. how realistic the simulators feel for a human) still could be questioned if not further investigated and proven (Wynne, Beanland, and Salmon, 2019).

On the other hand, computer simulations can be used to run various tests with reasonable effort and time constraints, but rely heavily on models and assumptions - which are typically simplifying complex real-world problems, and therefore show a lower ecological validity compared to physical tests. Simulations can be divided into counterfactual simulations, that define and simulate situations based on data from real traffic (e.g. McLaughlin, Hankey, and Dingus, 2008; Van Auken et al., 2011; Gorman, Kusano, and Gabler, 2013; Rosen, 2013; Bärgman, Lisovskaja, et al., 2015 or Bärgman, Boda, and Dozza, 2017) and artificial scenario set-ups, where artificial situations are created and simulated (e.g. Dobberstein et al., 2017; Jeong and Oh, 2017; Yanagisawa et al., 2017 or L. Wang et al., 2018).

The quality of the simulation results is influenced by two key elements: the model of the proposed system (i.e. how well does the model represent the actual ADAS) and the ecological validity of the simulation (i.e. how well can the simulation represent reality). A factor that is typically limiting the ecological validity of the simulation is the availability of detailed driver models for the specific target scenarios (Bärgman, Boda, and Dozza, 2017). Driver models can describe the behaviour of the driver (e.g. reaction to a warning or a critical situation) in the situation the system is designed for, and therefore improve the results of the simulation as a typical human behaviour is included and considered. In this way, not only the system itself is tested, but also how the system works in combination with a human driver. Lundgren and Tapani (2006), Markkula (2015) and Bärgman, Boda, and Dozza (2017) have shown that the accuracy of driver models in reproducing driver behaviour has a strong influence on the output quality of the simulation. However, no detailed driver models of the truck drivers behaviour are available, neither in general nor for specific target scenarios. This lack of driver models results in simulations with a low ecological validity, especially when driver reactions are prompted such as from a Frontal Collision Warning (FCW) system.

Although several safety benefit assessment approaches have been proposed (Carter et al., 2009; Yves et al., 2015; Sander, 2018), to date, no standardised procedure or framework is available that would provide a best-practice approach to a holistic safety benefit estimation. Typically, these assessments are rather performed individually and independently of each other and their results not combined into a common benefit estimation. For example, Bayly et al. (2007) performed a detailed analysis of multiple data sources for assessing the effectiveness of ADAS, but lack a combination of any of the data sources to a common output and rather report all results individually. This compartmentalised analysis of results hinders the identification of the overall safety benefit. Therefore, there is a need for the development of a methodology that could combine different results into a common safety benefit assessment, coupling the advantages of several approaches while mitigating the negative consequences.

1.3 Aim and objectives

Based on the previously described considerations, the scope of the overall PhD project is to provide a complete safety benefit assessment framework for heavy trucks. The foreseen steps to reach the scope are to:

- Provide a framework that can incorporate multiple data sources and combine their results into one common safety benefit output for a specific safety system;
- Apply the framework and identify possible areas of improvements, i.e. how can the output quality and validity of the framework be improved;
- Identify target scenarios for heavy trucks on European roads that should be addressed by ADAS and are the basis for the safety benefit assessment;
- Create driver behaviour models for truck drivers in the specified target scenarios;
- Implement the improvements and driver models into the framework, to perform the safety benefit assessment associated to the introduction of new ADAS for long-haul trucks.

The licentiate thesis at hand presents the first steps to achieve the scope and addresses the first three objectives.

2 Method and Data Sources

The objectives of this thesis are to provide a safety benefit assessment framework that can incorporate multiple data sources and to prepare the application of the framework to new ADAS for long-haul trucks. The methodology and data sources used to reach the objectives of the licentiate thesis are described in the following chapter.

2.1 Bayesian inference

To reach the first of the previously described objectives, the framework itself needs to be designed. The goal of the framework is to provide a safety benefit estimation for a specific ADAS (i.e. to estimate the change in injury outcome) that is as accurate as possible and also feasible in a timely and economical manner, incorporating knowledge from different data sources (e.g. simulations and physical tests). In addition, the framework should allow for previous results to be updated with new results, so that the assessment phase does not need to be completely repeated when new data is available. A mathematical model that fits these requirements is Bayesian inference. Applying Bayesian inference for the combination of results from different sources (e.g. simulation and test results) in the assessment of ADAS systems can be motivated by the fact that Bayesian inference is a mathematically optimal way of updating prior information with new observations (Hoff, 2009). The theoretical foundations and applications of Bayesian methods are described e.g. in Kruschke (2015) or Hoff (2009).

Bayesian inference is based on the two fundamental ideas of reallocation of credibility across possibilities and that these possibilities are meaningful parameters in mathematical models (Kruschke, 2015). As a simple example (adopted from Kruschke, 2015), one could imagine a situation where we are leaving our house. Once we stepped outside, we notice that the pavement in front of our building is wet and we wonder why. There can be multiple reasons for this, e.g. a shower of rain, a broken water pipe or a person that spilled a drink. If the only knowledge we have at this point is that the pavement is wet, all of these reasons (or possibilities) will have a certain probability, based on previous knowledge (e.g. rain might be deemed more probable than a broken water pipe based on previous experiences). However, once we step onto the pavement, we can make new observations. If not only the pavement, but also cars and trees are wet, more probability will be reallocated towards rain. On the other hand, if we see an empty bottle on the pavement and the wetness extends only to a small area, more probability would be reallocated towards the spilled drink hypothesis (even though it might have had a very low prior probability). This procedure of reallocation of probability (or credibility in a more everyday term) is the essence of Bayesian inference (Kruschke, 2015). Bayesian inference has already been used in various contexts, see Gårder, Leden, and Pulkkinen (1998) or Hauer (1983a). However, using Bayesian inference for combining different assessment methods, e.g. defining a prior distribution based on simulation results and updating this information with real-world test results, is new and is further explained in Chapter 4.1.

2.2 Multilevel crash data analysis

In order to improve the output quality of the framework (addressing the second of the previously described objectives, see Chapter 1), detailed driver models should be implemented into the simulations of the newly introduced ADAS for trucks (see also Lundgren and Tapani, 2006; Markkula, 2015 or Bärgman, Boda, and Dozza, 2017). These models are designed for and only valid in specific target scenarios, e.g. a rear-end situation where the ego vehicle is approaching a slower target vehicle ahead. It is therefore important to identify the most frequent and critical target scenarios by analysing crash data, so that the system development and driver models can be focused on those. As a detailed up-to-date analysis of European crash data that could support the target scenario identification for heavy trucks is missing, the following crash data analysis was performed.

The basis for the identification of the target scenarios was a three-level analysis of crash data (see Figure 2.1). The first level was European crash data from the Community Database on Accidents on the Roads in Europe (CARE), which aggregates crash data on a European level. This database contains general estimates from police-reported crash data that is supplied by all EU member states (European Commission Directorate General for Mobility and Transport, 2018), thereby providing high-level crash data for all of Europe. In addition to the injury classification used within CARE (fatal, severe, slight), the union of fatal and severe injuries will be used (KSI - killed or severely injured) to include all crashes with severe consequences in the same category. More details on the set of variables contained in CARE are specified in the common accident data set glossary (European Commission Directorate General for Mobility and Transport, 2019a). The analysis of CARE provides the largest crash data set with a general overview of HGV-involved crashes on EU-level, but has a too low degree of detail to identify critical crash scenarios. As CARE only contains general data (e.g. weather, time, road surface condition) and information such as vehicle weight or crash scenario are unreliable and not fully available, this data set needs to be complemented by more detailed data sources.

Therefore, in a next step, national crash databases from Sweden (see Transportstyrelsen, 2019), Italy (see Instituto Nazionale di Statistica, 2019) and Spain (see Dirección General de Tráfico, 2019) were used for the second level of analysis. These types of databases have a higher grade of detail compared to CARE and allowed the identification of cases where trucks with a weight above 16t (later referred to as 16t+ trucks) were involved in the crash. This classification is based on the scope of the project and aims to exclude light and short goods vehicles such as vans that have a completely different architecture from long-haul trucks, see also Sandin et al. (2014). These databases also allowed the identification of typical crash scenarios for 16t+ trucks.

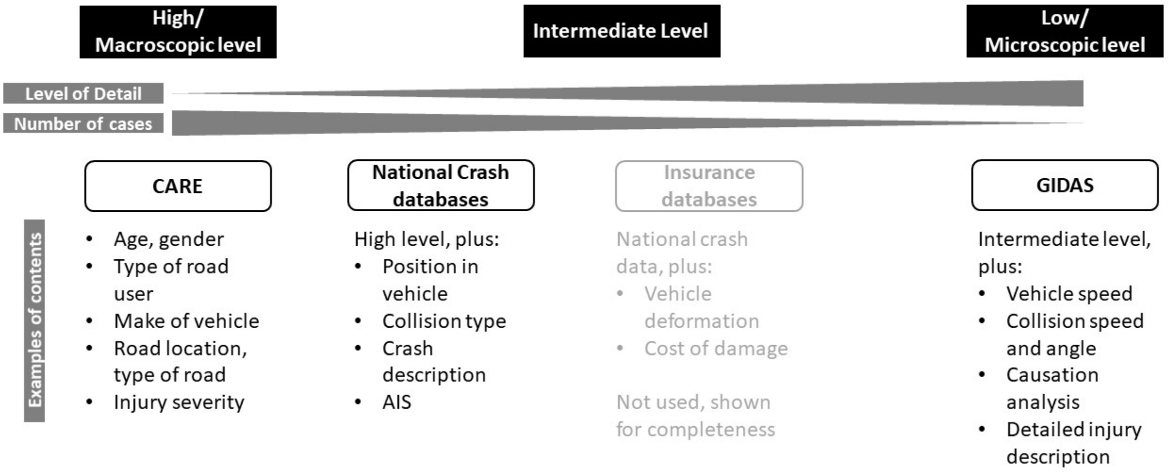

Figure 2.1: Overview of databases used in the HGV crash data analysis, from Schindler et al. (2020)

The third level of the analysis examined in-depth crash data from the German In-Depth Accident Study (GIDAS), that contains even more detailed information not available from the previous databases (e.g. simulation of pre-crash events in the GIDAS-Pre Crash Matrix (GIDAS-PCM) and an accident causation analysis system (ACAS)). The data is collected by special investigators in the German regions around Hannover and Dresden. The investigators are informed about a crash in their respective region at the same time as the police and go out to the crash scene to collect detailed data, including measurements inside and outside the vehicle (e.g. seating position, skid marks). Trained medical personnel collects detailed information on injuries (in collaboration with the hospitals) and interviews the persons involved in the crash. All this information is the basis for the pre-crash simulation that contains a five second reconstruction of the pre-crash events (Schubert, Liers, and Petzold, 2017), as well as the causation analysis ACAS.

Within ACAS, the classification is divided into three top-level domains: (a) human failure (e.g. inattention, drowsiness), (b) vehicle failure (e.g. technical malfunctions, illegal modifications) and (c) environmental influences (e.g. infrastructural failures, weather influences). Each of these factors (a)-(c) is broken down into different categories, which in turn are organised into different criteria, that are further divided into several indicators, increasing the grade of detail in each step (for an example, see Figure 2.2).

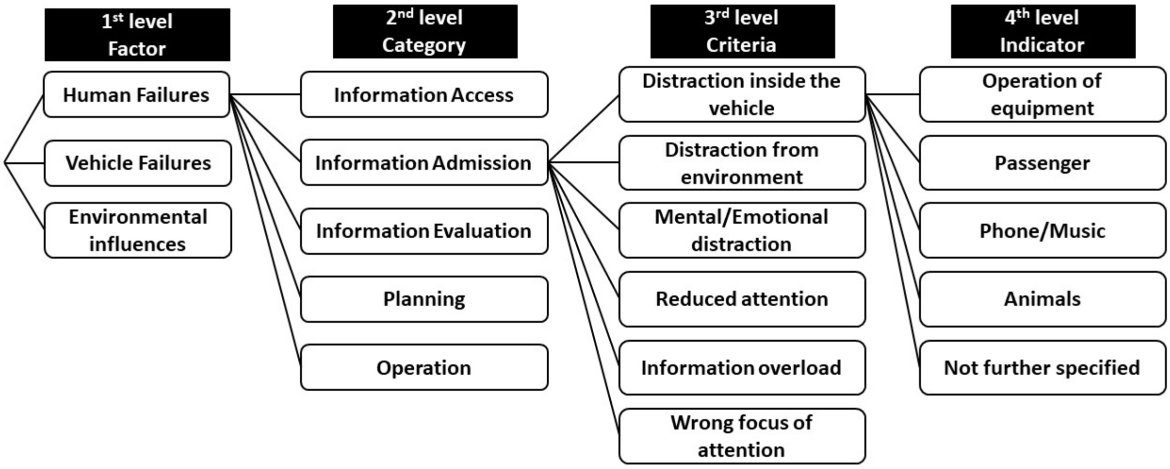

Figure 2.2: Example of ACAS classification, from Schindler et al. (2020)

The following chapter contains a short summary of the appended papers. The final framework and a first application to ADAS for cars as well as the results from the three-level crash data analysis are presented in Chapter 4.

3 Summary of Papers

This chapter gives a short overview of the appended papers. After the overview of the papers and the authors contribution, an extended abstract of each paper is presented.

Paper I

Kovaceva, J.; Bálint, A.; **Schindler, R.** and Schneider, A. (2020). Safety benefit assessment of autonomous emergency braking and steering systems for the protection of cyclists and pedestrians based on a combination of computer simulation and real-world test results. *Accident Analysis & Prevention, 136*, 105352.

Author's contribution: contributed in the set-up of the safety benefit evaluation framework and writing the paper, with specific contributions to the literature review and incorporation of market penetration and user acceptance in the framework. Responsible for conclusions together with other authors.

Paper II

Schindler, R.; Jänsch, M.; Johannsen, H. and Bálint, A. (2020). Understanding European heavy goods vehicle crashes using a three-level analysis of crash data. *Under review at Accident Analysis & Prevention*
A shorter version of this paper was accepted after peer-review for the Transport Research Arena (TRA) 2020 conference in Helsinki, Finland, and will be presented in April 2020.

Author's contribution: Main author, responsible for the study setup and coordinator for the contributions of co-authors. Extraction and analysis of European crash data and Swedish national crash data, analysis of Italian and Spanish crash data. Writing largest part of the paper, responsible for conclusions together with other authors.

Paper I: Safety benefit assessment of autonomous emergency braking and steering systems for the protection of cyclists and pedestrians based on a combination of computer simulation and real-world test results

Introduction

Cyclists and pedestrians account for a significant share of fatalities and serious injuries in the road transport system. In order to protect them, advanced driver assistance systems are being developed and introduced to the market, including autonomous emergency braking and steering systems (AEBSS) that autonomously perform braking or an evasive manoeuvre by steering in case of a pending collision, in order to avoid the collision or mitigate its severity.

Method

This study proposes a new prospective framework for quantifying safety benefit of AEBSS for the protection of cyclists and pedestrians in terms of saved lives and reduction in the number of people suffering serious injuries. The core of the framework is a novel application of Bayesian inference in such a way that prior information from counterfactual simulation is updated with new observations from real-world testing of a prototype AEBSS.

Results

As an illustration of the method, the framework is applied for safety benefit assessment of the AEBSS developed in the European Union (EU) project PROSPECT. In this application of the framework, counterfactual simulation results based on the German In-Depth Accident Study Pre-Crash Matrix (GIDAS-PCM) data were combined with results from real-world tests on proving grounds.

Conclusions

An assessment framework was defined in this paper to prospectively estimate the safety benefit. The core of the assessment framework is a Bayesian update of prior information from simulation with new observations from real-world testing. The presented benefit assessment framework can be used in future studies, and the results have potential implications for policies and regulations in understanding the real-world benefit of new active safety systems. Additionally, the Bayesian modelling approach of defining priors based on initial information of potentially lower fidelity and updating it with results of presumably high fidelity used in this paper has a great potential to be used in other studies.

Practical Applications

The proposed framework gives a systematic way for the combination of results from different sources and can be considered for understanding the real-world benefit of new ADAS systems.

Paper II: Understanding European heavy goods vehicle crashes using a three-level analysis of crash data

Introduction

In 2015, heavy goods vehicles (HGVs) were involved in 4.5% of police-reported road crashes in Europe and 14.2% of fatal road crashes. Active and passive safety systems can help to prevent crashes or mitigate the consequences but need detailed scenarios based on analysis of region-specific data to be designed effectively. The aim of this paper is to give a comprehensive and up-to-date analysis of HGV crashes in Europe.

Method

The identification of the most critical scenarios and their characteristics is based on a three-level analysis by including general HGV crash statistics from CARE, results about trucks weighing 16 tons or more from national crash databases and a detailed study of in-depth crash data from GIDAS, including a crash causation analysis.

Results

Most European HGV crashes occur during clear weather conditions, during daylight, on dry roads, outside city limits, and on non-highway roads. Three scenarios that should be addressed by future safety systems are identified and characterized in-depth: (1) rear-end crashes with other vehicles in which the truck is the striking partner, (2) conflicts during right turn maneuvers of the truck and a cyclist riding alongside and (3) pedestrians crossing the road in front of the truck.

Conclusions

The three levels of data analysis used in this paper give a deeper understanding of European HGV crashes, in terms of the most common crash characteristics on EU level and detailed descriptions of both kinematic parameters and crash causation for the above scenarios (1)-(3). This approach ensures both a global overview and sufficient depth of analysis in the most relevant cases.

Practical Applications

Developers can use the detailed scenario characterizations to improve their systems by focusing on the most relevant crash situations and achieve the highest benefits. The results give essential input to the EU project AEROFLEX for the development of an improved HGV front-end. The results can be used to set-up test-protocols for heavy trucks (similarly to Euro NCAP protocols for cars).

4 Results

In Chapter 2, the requirements on the framework for a safety benefit estimation by combination of information from different data sources have been defined. In this chapter, the realisation of the framework through a Bayesian statistical approach is described. An application of the framework can be found in Paper I. Furthermore, the results of the crash data analysis of Paper II are shortly presented, including the identified target scenarios.

4.1 Bayesian framework

In order to obtain accurate performance information on the ADAS, the proposed framework combines results from simulations and real-world testing in a systematic way, by using a Bayesian statistical approach (see Figure 4.1). The basis of the framework is an analysis of real-world crash data that aims to identify and describe the most common and critical crash scenarios. These scenarios are used for the selection of the target scenarios in which the new ADAS should work and be tested. As simulation results of the new systems are typically available earlier than physical test results, the outcome of the simulation is used as the prior information in the Bayesian model. Within the model, these results are then updated by incorporating the test results to obtain a posterior benefit estimation from both sets of results (see Figure 4.1). In addition, a weighting between prior information and new observations that can reflect different degrees of trust in the different data types and results can be incorporated.

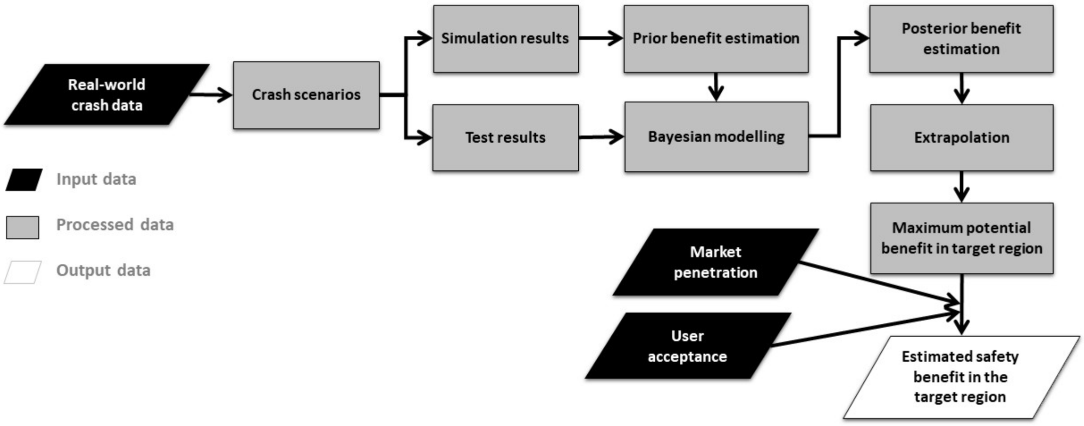

Figure 4.1: The proposed framework for the safety benefit assessment, adopted from Kovaceva et al. (2020)

As the simulation results (especially counterfactual simulations) are typically based on regionally limited data (e.g. GIDAS data from the the two German regions where the data is collected), the results need to be extrapolated to the target population or region (e.g. Europe), for example with a decision tree method (see Kreiss et al., 2015) or iterative proportional fitting procedure (see Niebuhr, Kreiss, and Achmus 2013), using crash data from different sources.

Important factors influencing the real world safety benefit of ADAS are market penetration (percentage of vehicles in traffic that are equipped with the system) and user acceptance (conditional probability that the system is used by the driver, i.e. not turned off, given that it is installed in a vehicle). If information on market penetration and user acceptance are available, the ecological validity of the extrapolation results can be further increased, as the results of the framework (posterior benefit) would incorporate a more realistic implementation of the system. If no information on market penetration and user acceptance is available, the output of the framework is a maximum potential safety benefit estimation (that would correspond to 100% market penetration and user acceptance). In the end, the reduction in injury outcomes achieved by the system can be translated to a monetary benefit, incorporating injury related costs such as used in Bühne et al. (2012).

The developed framework is able to estimate the safety benefit of a proposed ADAS, but the quality of the estimation output is strongly dependent on the accuracy and degree of detail of the provided input (see also Figure 4.1). As described in the method section (see Chapter 2), the ecological validity of the simulation results (third box in Figure 4.1) can be improved by including detailed driver models.

In principle, the framework is flexible and applicable to many types of systems and road users, as the application to multiple ADAS systems for cars in Paper I has exemplified. In order to identify and study the most critical target scenarios for heavy trucks that should be addressed by ADAS (and for which driver models should be developed), the crash data analysis within Paper II was performed.

4.2 Target scenarios and conditions

Most of the crashes that involve 16t+ trucks occur during dry and clear weather conditions (76%-88%, depending on region), during daylight conditions (73%-78%) and on dry roads (51%-83%), outside city limits (57%-87%) on non-highway roads (54%-81%). With regards to injuries on a European level, car occupants account for the highest number of killed or severely injured (KSI) road users with 48%, followed by vulnerable road users (VRUs) with 25%. It is notable that among all injuries, VRUs account for 16%, whereas for KSI they account for 25% (whereas the share of car and truck occupants reduces from all injuries to KSI).

Figure 4.2 shows the subset of the most frequent crash scenarios in the GIDAS in-depth database that has been used to investigate the different crash scenarios in more detail. The reported numbers are the absolute numbers of 16t+ trucks involved in a crash recorded in GIDAS (i.e. one crash with for example two 16t+ trucks involved would be counted as two cases in this analysis). The overall 1091 case counts, where a 16t+ truck was involved, are divided by crash opponents and further broken down into crash types. For these subcategories, their share within the respective previous category is represented by the given percentages (e.g. rear-end crashes between 16t+ trucks and cars account for 97 cases, which are 8.9% of all cases (black rhombus), 19.9% of the crashes between a 16t+ truck and a car (blue circle) and 35.7% of the crashes between a 16t+ truck and a car in longitudinal traffic (red triangle)). Overall, rear-end crashes with cars and commercial vehicles (e.g. busses and trucks) make up 20.1% of all crashes. Although cases with cyclists and pedestrians have a lower frequency (accounting for 8.8% of crashes and 5.1% respectively), their injury outcome is especially severe due to the high mass difference between the truck and VRU, as well as the lack of a protective shell around the VRU.

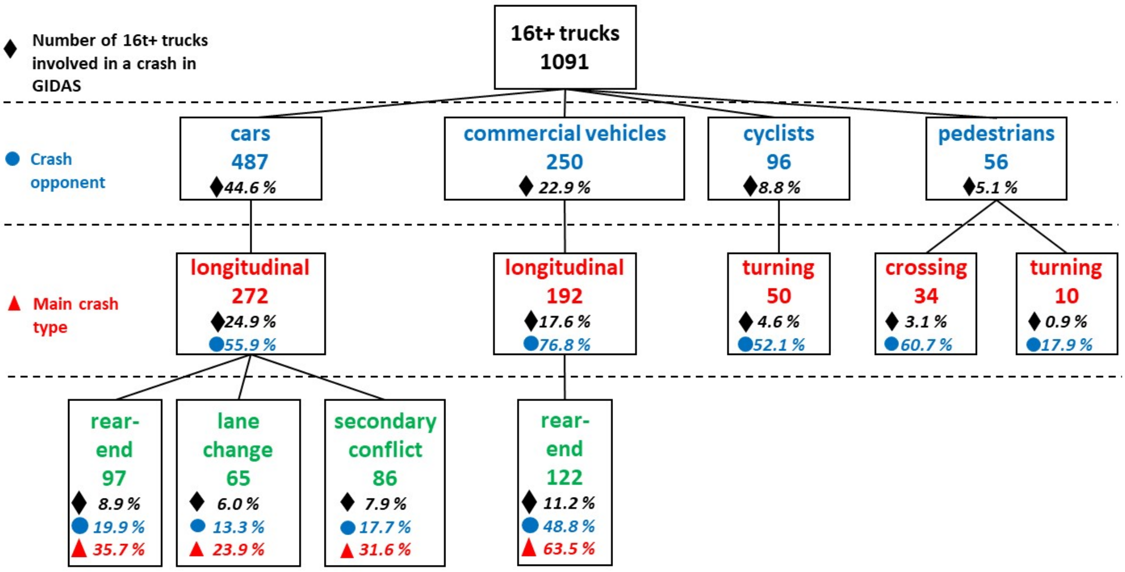

Figure 4.2: Subset of the most frequent crash types by crash opponent and crash type from GIDAS (case count and percentages per category), from Schindler et al. (2020)

As a result of the three-stage analysis performed in Paper II, three critical scenarios were identified: (1) rear-end crashes with other vehicles in which the truck is the striking vehicle, (2) crashes between trucks and cyclists, during right turn manoeuvres of the truck, while a cyclist is travelling alongside with the intention to go straight and (3) crashes between trucks and pedestrians, where the pedestrian is crossing the road perpendicular to the direction of travel of the truck. These scenarios address the three different road user types, with scenario 1 as the overall most frequent one and scenarios 2 and 3 as the most frequent crash scenarios with VRUs as the crash opponent, in line with the projects' focus on improved safety for cyclists and pedestrians in the interaction with trucks.

These scenarios should be addressed by future research and ADAS and were therefore studied in more detail in the GIDAS database. The analysis lead to the following general conclusions (for more details, please see Paper II):

(1) In rear-end crashes, the average speed reduction of the striking vehicle between onset of conflict and collision is 20 km/h. On average, the impact speed of the truck is 30 km/h and the lead vehicle is typically standing still. According to the ACAS classification, human failures were identified as the main contributing factor to the crash in 95% of cases, with the category information admission (e.g. distraction) identified as the most common category in 72% of cases.

(2) During right turn manoeuvres, the average collision speed of the truck is generally low (about 13 km/h) due to the nature of the turning manoeuvre. The impact point of the cyclist with the truck is typically within the first 2 m along the length of the truck (i.e. around the area of the passenger-side door) at an angle of 33 degrees on average. According to the ACAS classification, problems with information access (e.g. not seeing the cyclist in the blind spot) were identified as most common in 72% of cases for the truck drivers in this scenario, and the cyclist was identified as the party at fault in 27% of all crashes.

(3) In the pedestrian crossing scenario, a separation into two cases can be made, depending on whether the pedestrian was overrun by the truck or not. In cases where the pedestrian is overrun by the truck, speeds are generally below 5 km/h, often resulting from situations when the VRU crosses in front of a standing truck and is not seen by the truck driver when the latter starts to accelerate. When the pedestrian is not overrun, collision speeds are generally higher (above 20 km/h), resulting in a deflection of the body to the front or side of the truck. In the pedestrian crossing scenario, problems with information admission were identified as the main causing factor in 50% of cases for the pedestrians. The outcomes in this scenario are particularly severe even at low speeds, especially when the VRUs are overrun by the truck.

5 Discussion

In this thesis, a Bayesian framework as a way of combining simulation and test results has been proposed for the safety benefit estimation of ADAS. Bayesian methods have been used in various fields before and proven their effectiveness, see for example Miaou and Lord (2003); Mitra and Washington (2007); Huang and Abdel-Aty (2010); Xie et al. (2018), including research on traffic safety by Hauer (1983a); Hauer (1983b); Gårder, Leden, and Pulkkinen (1998) and Morando (2019). The research in this thesis has shown that the application of Bayesian inference can be extended from incorporating multiple outcomes of one data source (e.g. quantitative expert judgement model, see Gårder, Leden, and Pulkkinen, 1998) to a novel combination of the outcomes of different and independent data sources into one common output. Paper I shows how the framework can be applied for the benefit estimation in traffic safety research and illustrates its use based on the European project PROSPECT.

A sensitivity analysis performed on different parameters influencing the model and possibly the results (e.g. different weight between test results and simulation results, i.e. between new observations and the prior) showed maximum deviations of the results of around 6% between more extreme cases (e.g. between a weight of 0 and 10). The application of the framework to the safety benefit assessment of four different ADAS for cars in Paper I shows its flexibility. The developed framework is not limited to specific systems, vehicles or target scenarios, but can freely be adapted to the user's needs.

The advantage of the Bayesian framework is that it provides a large amount of information regarding the distribution of model parameters. In contrary to, for example, classical null-hypothesis significance testing, the output is not only a single number (i.e. p-value) on which a decision is based, but rather a distribution of the relevant parameters. Furthermore, uncertainties in the model parameters can be incorporated through the chosen distributions (e.g. higher or lower variance can be included). In the end, the posterior distribution of each modelled parameter is available, and can therefore show tendencies in the data clearer - and can be the basis for a more informed decision.

Moreover, the information of different data sources can be weighted against each other. If there are strong indications that real-world test results are more reliable than simulations, or that the latest generation of the prototype will perform in a more realistic manner than the first, these can be incorporated into the framework. However, the specification of prior distributions and weights as well as a sensitivity analysis need to be part of every analysis to ensure transparency towards the obtained results, i.e. providing the possibility to retrace what was done.

The data within the framework can be continuously updated, either as new information becomes available or a new type of input is provided. The obtained posterior distributions can become the new prior assumptions, which provides an easy and straightforward way to include previous knowledge in future research.

Market penetration and user acceptance of the evaluated systems depend on several factors, such as the design of the system itself, laws and regulations, results of consumer testing protocols (such as Euro NCAP) or the implementation strategy of the manufacturers (e.g. basic equipment or optional, possibility to turn it off) as well as their marketing. The linear relationship between user acceptance and market penetration towards the reduction of casualties used in Paper I may be an oversimplification according to Sander (2018). Modelling the dependence on these two parameters, for example by implementing collected market penetration or user acceptance data points of similar systems through statistical modelling, should be refined in future research to improve the output quality of the framework.

Although this framework can incorporate different information sources and provide a detailed output, the quality of the output itself is strongly depending on the quality of the input. If the data input has poor quality, e.g. simulation results are not representative for the actual function of the system or the real world, the framework is not able to fully compensate this limitation - it would require a very large sample of test results to compensate for this issue, which may not be feasible to obtain. If detailed driver models can be incorporated into the simulations, their reliability would increase and they could provide a more trusted input to the framework (see Lundgren and Tapani, 2006 or Markkula, 2015). Even for autonomous systems such as AEBS, driver models can help to improve acceptance of the system, e.g. by providing input during the development process (adequate information/warning timings, expected behaviour of the system by the driver). Although there is some leeway for compensation within the framework by setting high values of the weight parameters, providing a high quality input is much more beneficial.

Especially for truck drivers, detailed driver models are not available, lagging behind the advances in system development and car driver behaviour modelling. Knight et al. (2008) had identified a lack of European crash data for heavy trucks that could support the definition of target scenarios and development of driver models. Although there is a wide knowledge base in North America, the applicability of this information to Europe might be limited (M.-H. Wang and Wei, 2016) due to different vehicle and infrastructure design as well as cultural backgrounds. Therefore, this thesis took the first step towards creating the necessary driver models by identifying the most critical target scenarios from European crash data. These target scenarios will later be used to improve the simulation results, and thereby the output quality of the framework for long-haul trucks.

The results that describe the general crash situation, obtained in the crash data analysis (see Paper II) and presented in Chapter 4, are specifically applicable to Europe and are similar to the findings of previous studies in the US, such as Zhu and Srinivasan (2011) who identified collisions in longitudinal traffic and collisions at intersections as the most common crash types. Kockum et al. (2017) had identified cars and other HGVs as the most common collision partners, and these findings are supported by the outcomes of the analysis at hand. The causation analysis of this thesis supplements the existing knowledge and provides a more detailed picture of how and why the crashes happen. This information is useful for system designers and original equipment manufacturers (OEMs), as it helps to identify in which areas the drivers need support.

All three analysis levels (CARE, national databases and GIDAS) show similar distributions regarding the analysed variables (e.g. environmental conditions, injury distributions, crash scenarios), although small differences exist. These differences could originate from local effects (different exposure, e.g. weather, driving behaviour, vehicle types) or filter criteria in each database (e.g. weight or size restrictions, vehicle classification, coding schemes). In addition, little reliable information on driver behaviour and pre-crash events is available from crash data, since the data collection is based on interviews and measurements that are performed after the crash has happened.

A limitation regarding the application of the proposed framework in Paper I is that a single in-depth data source may not capture all relevant aspects of the crash population in the target region. The proposed three-step analysis in Paper II as well as the used extrapolation method in Paper I are able to correct for some of the differences in terms of the variables used in the process (e.g. different population or weather conditions), but are not able to account for all differences. In future applications of the framework, this aspect could be improved by using in-depth crash data from several different regions that may allow the characterisation of relevant local differences within the target region.

The implementation of ADAS in trucks can help to improve the traffic safety of heavy goods vehicles. This thesis provides a framework that can be used to identify the most promising systems (i.e. the systems with the highest safety benefit), based on a combination of various data inputs such as simulations and experiments. Furthermore, this thesis shows that there are input parts of the framework that need further improvements, and initiates the steps to provide these improvements. Target scenarios are identified, that will be the basis for a data collection on driver behaviour, that will in turn be used for the development of driver models.

6 Conclusions

An assessment framework was defined as part of this thesis to prospectively estimate the safety benefit of advanced driver assistance systems. The core of the assessment framework is a Bayesian update of prior information (e.g. results from simulations) with new observations (e.g. results from real-world testing). The framework was applied for the safety benefit assessment of the ADAS developed in the PROSPECT project and a sensitivity analysis was conducted, showing relatively little sensitivity of the results on the main assumptions made. The presented benefit assessment framework can be used in future studies, and the results have potential implications for policies and regulations in understanding the real-world benefit of new safety systems. Additionally, the framework has shown a new promising application of Bayesian inference. The approach of defining priors based on initial information of lower reliability and updating them with results of higher reliability presented in Paper I has a great potential to be used for other studies and applications.

For the application of the prospective safety benefit assessment framework to long-haul trucks, the most critical crash scenarios that involve heavy trucks with a weight above 16t on European roads were identified. A comprehensive crash data analysis was conducted simultaneously on three levels (see Figure 2.1) and was supplemented by a crash causation analysis. It was found that most crashes occur during dry and clear weather conditions (76%-88%, depending on region), during daylight conditions (73%-78%) and on dry roads (51%-83%), outside city limits (57%-87%) on non-highway roads (54%-81%). All three analysis levels show the same trends regarding these variables, but small differences exist. The reasons for these differences could range from local effects (e.g. weather, driving behaviour, vehicle types) to filter criteria in each database (e.g. weight or size restrictions). In most cases analysed in more detail, human errors were identified as the main contributing factor to the crash. This crash data can further provide an input to the safety system development.

The identified, most frequent and critical target scenarios are (a) rear-end crashes with the truck as the striking vehicle, (b) crashes between a right-turning truck and adjacent cyclist and (c) crashes between a truck and a pedestrian crossing in front of the truck. These three scenarios should be the basis for ADAS development and further addressed by driver behaviour modelling in the future.

In the future, data on truck driver behaviour should be collected and analysed. This data can be the basis for truck driver behaviour modelling. These models should be implemented into simulations and can improve their validity. In the end, these advances will also improve the output quality and accuracy of the overall framework.

References

Alm, H. and L. Nilsson (1994). Changes in driver behaviour as a function of handsfree mobile phones—A simulator study. *Accident Analysis & Prevention* **26**.4, 441–451.

Bärgman, J., C.-N. Boda, and M. Dozza (2017). Counterfactual simulations applied to SHRP2 crashes: The effect of driver behavior models on safety benefit estimations of intelligent safety systems. *Accident Analysis & Prevention* **102**, 165–180.

Bärgman, J., V. Lisovskaja, et al. (2015). How does glance behavior influence crash and injury risk? A 'what-if'counterfactual simulation using crashes and near-crashes from SHRP2. *Transportation Research Part F: Traffic Psychology and Behaviour* **35**, 152–169.

Bayly, M. et al. (2007). Review of crash effectiveness of intelligent transport systems. *Emergency* **3**, 14.

Bertollini, G. et al. (1994). The general motors driving simulator. *SAE transactions*, 54–67.

Bühne, J.-A. et al. (2012). ASSESS deliverable D2. 2, Socio-economic impact of safety systems.

Carter, A. et al. (2009). "safety impact methodology (SIM): evaluation of pre-production systems". *Proceeding of the 21st International Technical Conference on the Enhanced Safety of Vehicles, Paper*. 09-0259.

Choi, S. et al. (2014). Assessing the Safety Benefit of Advanced Vehicular Technology for Protecting Pedestrians: Pedestrian Protection Airbags. *Transportation research record* **2464**.1, 52–58.

Cicchino, J. (2017). Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. *Accident Analysis & Prevention* **99**, 142–152.

Cicchino, J. (2018). Effects of lane departure warning on police-reported crash rates. *Journal of safety research* **66**, 61–70.

Dirección General de Tráfico (2019). *Accidentes con víctimas, fallecidos 30 días, heridos graves y leves.* `http://www.dgt.es/es/seguridad-vial/estadisticas-e-indicadores/accidentes-30dias/`. [Online; accessed 04-December-2019].

Dobberstein, J. et al. (2017). "The Eclipse Working Group openPASS–an open source approach to safety impact assessment via simulation". *25th International Technical Conference on the Enhanced Safety of Vehicles (ESV).*

Doyle, M., A. Edwards, and M. Avery (2015). "AEB real world validation using UK motor insurance claims data". *Proc. 24th ESV Conference*. 15-0058.

Edwards, M. et al. (2015). Assessment of integrated pedestrian protection systems with autonomous emergency braking (AEB) and passive safety components. *Traffic injury prevention* **16**.sup1, S2–S11.

European Commission Directorate General for Mobility and Transport (2018). *European Commission, Annual Accident Report 2018.* `https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/statistics/dacota/asr2018.pdf`. [Online; accessed 21-November-2019].

European Commission Directorate General for Mobility and Transport (2019a). *Community database on Accidents on the Roads in Europe.* `https://ec.europa.eu/transport/road_safety/specialist/observatory/methodology_tools/about_care_en`. [Online; accessed 21-November-2019].

European Commission Directorate General for Mobility and Transport (2019b). *Road Safety - What we do.* `https://ec.europa.eu/transport/road_safety/what-we-do_en`. [Online; accessed 29-November-2019].

Evgenikos, P. et al. (2016). Characteristics and causes of heavy goods vehicles and buses accidents in Europe. *Transportation research procedia* **14**, 2158–2167.

Freeman, J. (1994). The Iowa driving simulator: a tool for human factors and vehicle virtual prototyping research. *International Journal of Heavy Vehicle Systems* **1**.2, 223–230.

Gårder, P. and M. Davies (2006). Safety effect of continuous shoulder rumble strips on rural interstates in Maine. *Transportation research record* **1953**.1, 156–162.

Gårder, P., L. Leden, and U. Pulkkinen (1998). Measuring the safety effect of raised bicycle crossings using a new research methodology. *Transportation Research Record* **1636**.1, 64–70.

Gorman, T., K. Kusano, and H. Gabler (2013). “Model of fleet-wide safety benefits of Lane Departure Warning systems”. *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013).* IEEE, pp. 372–377.

Hauer, E. (1983a). An application of the likelihood/Bayes approach to the estimation of safety countermeasure effectiveness. *Accident Analysis & Prevention* **15**.4, 287–298.

Hauer, E. (1983b). Reflections on methods of statistical inference in research on the effect of safety countermeasures. *Accident Analysis & Prevention* **15**.4, 275–285.

Hoff, P. (2009). *A first course in Bayesian statistical methods.* Vol. 580. Springer.

Huang, H. and M. Abdel-Aty (2010). Multilevel data and Bayesian analysis in traffic safety. *Accident Analysis & Prevention* **42**.6, 1556–1565.

Instituto Nazionale di Statistica (2019). *Survey on road accidents resulting in death or injury.* `http://siqual.istat.it/SIQual/visualizza.do?id=7777778`. [Online; accessed 04-December-2019].

Isaksson-Hellman, I. and M. Lindman (2016). Evaluation of the crash mitigation effect of low-speed automated emergency braking systems based on insurance claims data. *Traffic injury prevention* **17**.sup1, 42–47.

Jeong, E. and C. Oh (2017). Evaluating the effectiveness of active vehicle safety systems. *Accident Analysis & Prevention* **100**, 85–96.

Knight, I. et al. (2008). *Longer and/or longer and heavier goods vehicles (LHVs): a study of the likely effects if permitted in the UK.* PPR 285. Citeseer.

Kockum, S. et al. (2017). Volvo Trucks Safety Report 2017. *Volvo Trucks Accident Research Team.*

Kovaceva, J. et al. (2020). Safety benefit assessment of autonomous emergency braking and steering systems for the protection of cyclists and pedestrians based on a combination of computer simulation and real-world test results. *Accident Analysis & Prevention* **136**, 105352.

Kreiss, J.-P. et al. (2015). "Extrapolation of GIDAS accident data to Europe". *24th International Technical Conference on the Enhanced Safety of Vehicles (ESV).*

Kristianssen, A.-C. et al. (2018). Swedish Vision Zero policies for safety–A comparative policy content analysis. *Safety science* **103**, 260–269.

Kruschke, J. (2015). *Doing Bayesian data analysis: A tutorial with R, JAGS, and Stan (2nd eds.)*

Kuehn, M., T. Hummel, and J. Bende (2009). "Benefit estimation of advanced driver assistance systems for cars derived from real-life accidents". *21st International Technical Conference on the Enhanced Safety of Vehicles ESV.* Vol. 15, p. 18.

Lundgren, J. and A. Tapani (2006). Evaluation of safety effects of driver assistance systems through traffic simulation. *Transportation research record* **1953**.1, 81–88.

Malczyk, A. and M. Koch (2019). "Injuries to Heavy Truck Occupants–Severity, Patterns and Causation". *Proc. IRCOBI conference 2019.*

Markkula, G. (2015). *Driver behavior models for evaluating automotive active safety: From neural dynamics to vehicle dynamics.* Chalmers University of Technology.

McLaughlin, S., J. Hankey, and T. Dingus (2008). A method for evaluating collision avoidance systems using naturalistic driving data. *Accident Analysis & Prevention* **40**.1, 8–16.

Miaou, S.-P. and D. Lord (2003). Modeling traffic crash-flow relationships for intersections: dispersion parameter, functional form, and Bayes versus empirical Bayes methods. *Transportation Research Record* **1840**.1, 31–40.

Mitra, S. and S. Washington (2007). On the nature of over-dispersion in motor vehicle crash prediction models. *Accident Analysis & Prevention* **39**.3, 459–468.

Morando, A. (2019). Drivers' response to attentional demand in automated driving.

Niebuhr, T., J.-P. Kreiss, and S. Achmus (2013). "GIDAS-Aided quantification of the effectiveness of traffic safety measures in EU 27". *Proceedings of the 18th Conference on the Enhanced Safety of Vehicles-Nagoya.* 541.

Nilsson, L. (1993). “Behavioural research in an advanced driving simulator-experiences of the VTI system”. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting.* Vol. 37. 9. SAGE Publications Sage CA: Los Angeles, CA, pp. 612–616.

Noort, M. van, F. Faber, and T. Bakri (2012). *EuroFOT safety impact assessment method and results.* Tech. rep.

Persaud, B. et al. (2001). Safety effect of roundabout conversions in the united states: Empirical bayes observational before-after study. *Transportation Research Record* **1751**.1, 1–8.

Reed, M. and P. Green (1999). Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialling task. *Ergonomics* **42**.8, 1015–1037.

Rosen, E. (2013). “Autonomous emergency braking for vulnerable road users”. *Proceedings of IRCOBI conference*, pp. 618–627.

Sander, U. (2018). *Predicting Safety Benefits of Automated Emergency Braking at Intersections-Virtual simulations based on real-world accident data.* Chalmers University of Technology.

Sandin, J. et al. (2014). “Traffic safety of heavy goods vehicles and implications for high capacity transport vehicles”. *Transport Research Arena 2014, Paris.*

Schindler, R. et al. (2020). Understanding European heavy goods vehicle crashes using a three-level analysis of crash data. *under review at Accident Analysis & Prevention.*

Schubert, A., H. Liers, and M. Petzold (2017). The GIDAS pre-crash-matrix 2016. Innovations for standardized pre-crash-scenarios on the basis of the VUFO simulation model VAST. *Berichte der Bundesanstalt fuer Strassenwesen. Unterreihe Fahrzeugtechnik* 117.

Sternlund, S. et al. (2017). The effectiveness of lane departure warning systems—A reduction in real-world passenger car injury crashes. *Traffic injury prevention* **18**.2, 225–229.

Strandroth, J. (2009). In-depth analysis of accidents with heavy goods vehicles–Effects of measures promoting safe heavy goods traffic. 2009: 2.

Transportstyrelsen (2019). *Strada informationssystem.* `https://www.transportstyrelsen.se/sv/vagtrafik/statistik/Olycksstatistik/om-strada/`. [Online; accessed 04-December-2019].

Van Auken, R. et al. (2011). Advanced crash avoidance technologies (ACAT) program–final report of the Honda-DRI team, volume I: Executive summary and technical report. *Volume I: Executive Summary and Technical Report, DOT HS* **811**, 454.

Viano, D. (1991). Effectiveness of safety belts and airbags in preventing fatal injury. *SAE transactions*, 1332–1344.

Wang, L. et al. (2018). “Multi-functional open-source simulation platform for development and functional validation of ADAS and automated driving”. *Fahrerassistenzsysteme 2016.* Springer, pp. 135–148.

Wang, M.-H. and C.-H. Wei (2016). “Potential Safety Benefit of the Blind Spot Detection System for Large Trucks on the Vulnerable Road Users in Taiwan”. *MATEC Web of Conferences*. Vol. 81. EDP Sciences, p. 02007.

Wynne, R., V. Beanland, and P. Salmon (2019). Systematic review of driving simulator validation studies. *Safety science* **117**, 138–151.

Xie, S. et al. (2018). Bayesian approach to model pedestrian crashes at signalized intersections with measurement errors in exposure. *Accident Analysis & Prevention* **121**, 285–294.

Yanagisawa, M. et al. (2017). *Estimation of potential safety benefits for pedestrian crash avoidance/mitigation systems.* Tech. rep. United States. National Highway Traffic Safety Administration.

Yves, P. et al. (2015). “A comprehensive and harmonized method for assessing the effectiveness of advanced driver assistance systems by virtual simulation: the PEARS initiative”. *The 24th international technical conference on the enhanced safety of vehicles (ESV).*

Zhu, X. and S. Srinivasan (2011). A comprehensive analysis of factors influencing the injury severity of large-truck crashes. *Accident Analysis & Prevention* **43**.1, 49–57.

Appendix