THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

in

Machine and Vehicle Systems

Analyzing real-world data to promote development of active safety systems that reduce car-to-vulnerable road user accidents

AZRA HABIBOVIĆ

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2012

Analyzing real-world data to promote development of active safety systems that reduce car-to-vulnerable road user accidents

AZRA HABIBOVIĆ
ISBN 978-91-7385-719-2

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 3400
ISSN: 0346-718X

Department of Applied Mechanics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31 7721000

Chalmers Reproservice
Gothenburg, Sweden, 2012

Mojim roditeljima.
(To my parents.)

Analyzing real-world data to promote development of active safety systems that reduce car-to-vulnerable road user accidents

Azra Habibović
Department of Applied Mechanics
Chalmers University of Technology

Abstract

The overall objective of the thesis is to explore various types of real-world road traffic data and to assess the extent to which they can inform the design of active safety systems that aim to prevent car-to-vulnerable road user (VRU) accidents. A combined analysis of in-depth and police reported accident data provided information on driver behavior and contextual variables, which is valuable for the development of active safety systems. An analysis of the in-depth data also revealed information about VRU behavior that is relevant for these systems. A key finding from these analyses is that the car drivers commonly did not see the VRUs due visual obstructions in the traffic environment, misinterpretation of the traffic situation, and/or an inadequate plan of action. The VRUs, on the other hand, saw the cars but they still misunderstood the situation, made an inadequate plan of action, or both.

These findings indicate that active safety systems should help drivers to notice the VRUs in time, while the VRUs would benefit from systems helping them to correctly understand the traffic situation. The findings also suggest a need for a variety of cooperative active safety systems, risk assessment algorithms able to predict the intentions of road users to cross the road, and human-machine interfaces capable of directing road users' attention towards the most critical event. Similar findings were obtained when driver behavior and contextual variables were investigated using video-recordings of car-to-pedestrian incidents. However, these data enabled more detailed analysis of driver attention allocation as well as driver interaction with the vehicle, other road users, and the traffic environment.

Finally, an analysis of data on pedestrian behavior and car dynamics from normal interactions in traffic showed that a statistical model, based on car speed and its distance to the point of potential collision and on pedestrian distance to the road, speed and head orientation, could be used to determine the likelihood of a pedestrian entering the road. This can then be combined with commonly used deterministic approaches to estimate when a warning or other action by an active safety system should be initiated. To conclude, each of the four data sources explored here has its own advantages and disadvantages; information combined from analysis of these sources provides an improved understanding of the traffic situations involving VRUs, which is crucial in the development of future active safety systems.

Keywords: Vulnerable road user (VRU), Causation analysis, Statistical analysis, Naturalistic observation, Driver behavior, VRU behavior, Functional requirements, Accident prevention, Active safety system

Acknowledgments

This work was carried out as a part of the project VISAS funded by the Swedish Agency for Innovation Systems (VINNOVA). Project partners were Volvo Car Corporation, Autoliv Electronics AB, and Chalmers University of Technology.

I would like to thank my academic supervisors Professor Mats Viberg and Assistant Professor Johan Davidsson at Chalmers University of Technology, for great discussions and scientific guidance. Johan deserves special gratitude for giving me the opportunity to work in this exciting field, providing me with endless support throughout my doctoral work, and encouraging me when things did not go my way. I would also like to thank my examiner, Professor Per Lövsund, at Chalmers for his advice on the general structure of this thesis. I am also grateful to Professors Kip Smith and Hans-Erik Pettersson for all of the discussions and advice related to road user behavior.

Jonas Bärgman and Karin Brolin at Chalmers are acknowledged for constructive support at the times when it was most needed. I thank Henrik Lind, Jonas Ekmark, Martin Magnusson, Anders Agnvall, John-Fredrik Grönvall, and Jordanka Kovaceva at Volvo Car Corporation for helping me with practical details in relation to the data extraction for the last paper in my thesis. My colleagues on the VISAS team and the staff members at Mindmancer AB provided valuable collaboration during the first two years of my work. Thanks also go to all members of the DREAMi project for constructive discussions and the wonderful time we have had. Great discussions with Mikael Ljung Aust and Helen Fagerlind at Chalmers are appreciated. Sonja Laakso Gustafsson is acknowledged for the valuable administrative support. I am grateful to Lora Sharp McQueen for teaching me the "art of writing" – without her tremendous editing work my papers and thesis would definitely not have been as clear.

I also thank my current and former colleagues at the Department of Applied Mechanics at Chalmers and SAFER – Vehicle and Traffic Centre at Chalmers, for creating a positive and inspiring work environment, and for making my long days shorter!

I am thankful that Vedo is still a part of my life in spite of all the hours that I spent at work. Thousands of thanks go to my family and friends for being there for me during this journey. In particular, I am sincerely grateful to my parents for always believing in me – without their encouragement I would never be where I am today. Od srca vam hvala za sve!

Appended papers

Paper I Habibovic, A., Davidsson, J., 2011. Requirements of a system to reduce car-to-vulnerable road user crashes in urban intersections. Accident Analysis and Prevention 43 (4), 1570-1580.

Contribution: Habibovic initiated the study, aggregated and interpreted the causation charts, extracted and analyzed the police reported data, derived requirements, and wrote the paper.

Paper II Habibovic, A., Davidsson, J., 2012. Causation mechanisms in car-to-vulnerable road user crashes: Implications for active safety systems. Accepted for publication in Accident Analysis and Prevention.

Contribution: Habibovic initiated the study, aggregated and interpreted the causation charts, derived requirements, and wrote the paper.

Paper III Habibovic, A., Tivesten, E., Uchida, N., Bärgman, J., Ljung Aust, M., 2012. Driver behavior in car-to-pedestrian incidents: An application of the Driving Reliability and Error Analysis Method (DREAM). Accepted for publication (with minor changes) in Accident Analysis and Prevention.

Contribution: Habibovic participated in the modification of DREAM, compilation of causation charts, and revision and aggregation of these. She interpreted the aggregated charts and their implication for the ADAS development, and wrote much of the paper.

Paper IV Habibovic, A., Viberg, M., 2012. Predicting the probability that a pedestrian will cross the road based on the data from onboard sensors. To be submitted.

Contribution: Habibovic initiated and designed the study, devised the annotation scheme for the data, annotated the data, carried out data modeling and interpretation, and wrote the paper.

Acronyms and definitions

Accident (Collision or Crash)	An unexpected and undesirable event involving any type of road user or road vehicle, resulting in property damage, injury, or both.
Active safety system	A safety countermeasure based on “intelligent” technology intended to prevent accidents by providing support to vehicle drivers and/or vulnerable road users.
Advance driver assistance system (ADAS)	An active safety system countermeasure based on “intelligent” technology intended to prevent accidents by providing support to vehicle drivers.
Driving reliability and error analysis method (DREAM)	A method for analysis of causation mechanisms based on a systemic accident model.
Functional requirements	A description of what a system is required to do. Functional requirements are the basis of the scope of the project work, defining user functions, system limitations, types of inputs and outputs.
Human machine interface (HMI)	Element or sub-element of an active safety system with which a driver or VRU can interact.
Incident (or conflict)	A traffic situation where two, or more, road users would have collided if at least one of them did not react.
Naturalistic observation	Study of road user behavior in naturalistic settings.
SafetyNet Accident Causation System (SNACS)	A version of DREAM that was used in the European project SafetyNet.
Vulnerable road user (VRU)	Pedestrians and bicyclists.

Table of contents

Abstract ..... **i**
Acknowledgments ..... **ii**
Appended papers ..... **iii**
Acronyms and definitions ..... **iv**
Table of contents ..... **v**
1 Introduction **1**
1.1 Background 1
1.2 Countermeasures to improve the safety of vulnerable road users 3
1.3 The role and principles of active safety systems 6
1.4 Design process for active safety systems 10
1.5 Real-world data sources for derivation of functional requirements 13
1.6 Methods for analysis of real-world traffic data 17
1.7 Aims 21
2 Summary of appended papers **23**
2.1 Paper I 23
2.2 Paper II 24
2.3 Paper III 25
2.4 Paper IV 26
3 Addendum: An example of a future active safety system **29**
3.1 Aim and outline 29
3.2 Functional requirements 29
3.3 Detection and tracking of the VRUs 31
3.4 Car position and velocity 31
3.5 Infrastructure-to-vehicle communication 32
3.6 Accident risk assessment 32
3.7 Human Machine Interface 33
3.8 Evaluation of the system proposed 34
3.9 Concluding remarks 35
4 General discussion **39**
4.1 Discussion of results 39
4.2 Methodological considerations 44
4.3 Directions for future active safety systems 50
4.4 Suggestions for future work 53
5 Conclusions **55**
6 References **57**

1 Introduction

1.1 Background

Rapid growth of the population, urbanization, and the need for mobility in recent decades have resulted in a tremendous expansion of road traffic in volume, intensity, and complexity. This has negative repercussions for the number of road accidents involving fatality and injury. Despite the fact that many countermeasures have been introduced to enhance road traffic safety, there are still more than 1.2 million fatalities and between 20 and 50 million injuries every year due to road traffic accidents worldwide (Peden et al., 2004; WHO, 2009).

Accidents between motor vehicles and vulnerable road users (VRUs), such as pedestrians and bicyclists, are especially frequent and severe. About a half of all road accidents involve VRUs (WHO, 2009). In the European Union 27 (EU-27), there were more than 320 000 VRU injuries and 10 000 VRU fatalities in 2008, which corresponds to approximately 20% of the total number of injuries and 26% of the total number of fatalities, Figure 1 (UNECE, 2008).

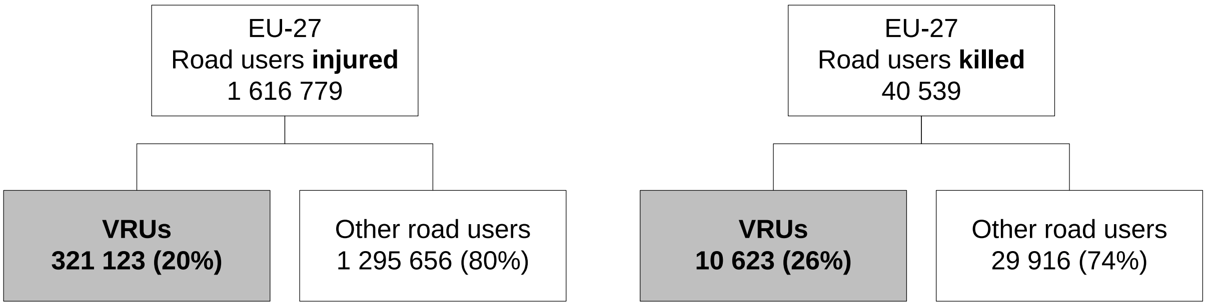

Figure 1. Distribution of injuries and fatalities in EU-27 for 2008 according to the road user type, based on the data extracted from the UNECE database.

In Sweden alone, over 3000 people were injured and 53 were killed in vehicle-to-VRU accidents during the year 2009, which corresponds to 12% and 15%, respectively, of the total number of injuries and fatalities in road traffic accidents (Trafikanalys, 2010). According to the National Highway Traffic Safety Administration (NHTSA, 2011), VRUs accounted for approximately 110 000 or 10% of all road traffic injuries and 4722 or 19% of all road traffic fatalities in the United States (US) in 2009. The situation is often worse in other countries around the world: reports by Singh (2005) and WHO (2009) show that VRUs constitute a much larger fraction of all road traffic related fatalities and injuries in developing countries, such as China and El Salvador, in comparison with industrialized countries. A comparison of VRU accident figures for selected countries is shown in Table 1.

In addition to the loss of human lives, accidents involving VRUs also imply a large societal and economic cost. The consequences of these crashes often result in the loss of workplace and household productivity. This becomes even more evident when it is taken into account that young persons are overrepresented in the vehicle-to-VRU crashes (Fröming et al., 2006; Habibovic, 2008; Toroyan and Peden, 2007).

Overall, these figures demonstrate an urgent need for countermeasures to improve the safety of VRUs; prevention of vehicle-to-VRU accidents would result in a reduction of not only causalities but also of societal and economic cost. In Sweden, the *Vision Zero* policy requires that the number of road traffic fatalities and serious injuries should eventually be reduced to zero (Johansson, 2009). In particular, a milestone for 2020 is a maximum of 220 fatalities per year. To achieve this goal, there is a need to understand the underlying mechanisms of accidents and injuries in order to suggest appropriate and effective countermeasures.

Table 1. Distribution of pedestrian and cyclist fatalities in selected countries. All data, except those for China, are for 2007. Data for China are from 2006 (WHO, 2009).

			Pedestrian fatalities		**Cyclist fatalities**	
Country	**Income**	**All fatalities**	*% of all fatalities*	*Per million inhabitants*	*% of all fatalities*	*Per million inhabitants*
Japan	High	6 639	32	17	13	7
Netherlands	High	791	12	6	24	12
Sweden	High	471	12	6	6	3
China	Middle	89 455	26	17	9	6
Cuba	Middle	994	33	29	14	12
El Salvador	Middle	1 493	63	137	4	9
Malawi	Low	839	45	27	18	11
Mozambique	Low	1 502	68	48	0	0
Rwanda	Low	308	40	13	18	6

In Sweden, approximately 16 000 or 80% of vehicle-to-VRU accidents involving injury or fatality that occurred between 2003 and 2007 were in urban areas (Habibovic, 2008). Similar figures are seen in other countries (Fröming et al., 2006; Andreone et al., 2006). The distributions observed are most probably due to the high complexity of traffic environment and the diversity of road users in urban areas (Archer and Vogel, 2000). Fortunately, a large proportion of these accidents only result in minor injuries; accidents in rural areas cause more severe and fatal injuries (Habibovic, 2008).

The distribution of accident severity between urban and rural areas can also be explained by the differences in vehicle speeds. The posted speed limits, and thereby vehicle speeds, are generally higher in rural areas. The injury severity level increases with increasing speed. In Sweden, approximately 13 300 or 65% of vehicle-to-VRU accidents that occurred between 2003 and 2007 were on roads with posted speed limits of 50 km/h or lower. Of these, about 97% caused injuries and 1% fatalities (Habibovic, 2008). However, more than 10% of accidents that occurred on roads with posted speed limits higher than 50 km/h were fatal.

A major proportion of the accidents involving VRUs that occur in urban areas are at intersections (Stutts et al., 1996; Fröming et al., 2006). In Sweden, approximately half of all vehicle-to-VRU accidents that occurred between 2003 and 2007 in urban areas were in intersections, or in relation to intersections (Habibovic, 2008).

Although different kinds of vehicles are involved in accidents with VRUs in urban intersections, several studies reveal that passenger cars are overrepresented. Habibovic (2008) showed that passenger cars accounted for over 70% of all accidents involving VRUs, which occurred in urban intersections in Sweden between 2003 and 2007. Also, in the majority of cases only one car was involved per accident.

The most frequent pre-crash scenario, with respect to car and VRU paths prior to accidents, varies for different countries. Although the scenario type was not assigned for many of the accidents analyzed in Habibovic (2008), it was noted that numerous car-to-pedestrian accidents in urban areas occurred when a pedestrian was crossing either after, or just before, an intersection where the car was going straight forward. The corresponding scenarios in the car-to-bicyclist accidents occurred when a bicyclist was coming from an intersecting road and either the bicyclist or the car was turning, or both were going straight forward.

In summary: *The epidemiology data indicate that the safety of VRUs must be improved, especially in urban areas. Safety for the VRU in intersections should be given priority. Car-to-VRU crashes are frequent and, in addition to the loss of human lives, often result in large economic and societal cost.*

1.2 Countermeasures to improve the safety of vulnerable road users

Compared with the safety of vehicle occupants, the safety of VRUs has been addressed less, especially prior to the early 1970s (Kjemtrup and Herrstedt, 1992; Mohan, 2008). In that time period, the growth in the number of vehicles was managed by expanding the infrastructure. Usually, this has led to increased exposure of the VRUs to vehicle traffic. The frequency and severity of the VRU accidents also increased, as a direct result of better roads which enabled higher vehicle speeds. During the 1970s, accident statistics showed that measures to improve the safety of VRUs were necessary (OECD, 1998).

Based on a literature survey (e.g., Almqvist and Hydén, 1994; Evans, 1990), it is possible to distinguish three broad categories of countermeasures with respect to the source that influences the VRU safety:

- traffic engineering and management,
- education and training for drivers and VRUs, and
- vehicle design engineering.

1.2.1 Traffic engineering and management

Traffic engineering measures include speed management, the separation of motor vehicle and VRU traffic, and the visibility enhancements of VRUs (Retting et al., 2003). Speed management incorporates components such as lane narrowing and speed bumps. Separation of VRUs from vehicle traffic is achieved mainly by engineering measures such as traffic signals, VRU overpasses, and sidewalks. The engineering measures designed to increase the visibility of VRUs include, for example, the installation and improvement of road lighting and removing vegetation. The traffic engineering measures have been widely applied and have shown a positive effect on the traffic safety (Retting et al., 2003).

1.2.2 The education of drivers and VRUs

The second approach, the education of VRUs and vehicle drivers in road safety, aims to improve their behavior by increasing knowledge and changing attitudes (Mohan, 2008). This approach has a long history; education programs addressing young children were, for instance, initiated in the Nordic countries over 40 years ago (OECD, 1998). Moreover, various public educational campaigns belong to this category of safety measures, for example, Koenig and Wu (1994) and Van Houten and Nau (1983). Today, traffic safety education in many countries is integrated in school programs. In some countries with a large proportion of elderly population, education for elderly VRUs and drivers has been initiated (OECD, 1998). The overall quality of driver education training is also significantly improved today compared with that of several decades ago.

The literature surveyed reveals differing opinions on the long-term effects of these measures on traffic safety. Some of the previously mentioned authors have shown major long-term effects, while some other authors, for example, Gregersen and Nolen (1994) and Sandels (1975), do not share this opinion.

1.2.3 Vehicle design engineering

Safety measures related to vehicle design engineering can be divided into two broad categories: passive and active. The passive measures aim to reduce accident severity. The attempts to protect VRUs by regulating the design of vehicles were rare until the 1980s. It was, in principle, only prohibited to attach sharp objects such as hood mascots to vehicles in order to reduce severity of VRU injuries in impacts with vehicles (McLean, 2005). The origin of this disregard was a societal view that the severity of VRU injuries caused by impact with a large and rigid vehicle was too great to be reduced by modifying vehicle design (Crandall et al., 2002; McLean, 2005).

The societal view has changed significantly in recent decades; the VRU safety discussions with regard to vehicle design have become frequent at both national and international levels. This has led to the introduction of regulations concerning VRU safety, such as 2003/102/EC in Europe and TRIAS63 in Japan. Globally harmonized requirements are also discussed, as described by Mizuno (2005). Other efforts made towards the improved safety of VRUs include standardized test programs by consumer driven safety organizations such as the New Car Assessment Programs (NCAP), (McLean, 2005). For example, based on adult and child head form and leg form impact tests, Euro NCAP has in 2009 introduced pedestrian protection rating as an integral part of their overall rating scheme for new cars (Euro NCAP, 2009).

Together, these safety efforts have, among others, resulted in an improved design of the front end of vehicles to promote VRU safety. The number of VRU fatalities and severe injuries has decreased tremendously during recent decades as a direct result of these improvements (Mizuno, 2005). Moreover, the development of several VRU protection systems based on "intelligent" technologies has been initiated to further minimize VRU injury severity in accidents. In this instance, intelligent technologies refer to various sensors, decision algorithms, and actuators onboard a car. Systems such as compliant bumpers, active hoods, and windscreen airbags belong to this category of safety systems. These systems are activated during or immediately prior to an accident and are generally referred to as passive safety systems.

The second category of vehicle engineering countermeasures, active safety systems, aims to prevent crashes from occurring, or to mitigate their severity. These systems have been in development for some time. One of the first, and probably the most widely used, active safety system is the anti-lock braking system (ABS), which has been on the market since the 1980s (Brookhuis et al., 2001). The ABS prevents the wheels from locking up when the driver is braking, and thereby enables the driver to maintain steering control of the car. Systems such as forward collision warning (FCW) and lane departure warning (LDW) also belong to this category of safety countermeasures.

At present, there is no standardized definition of what is included in this category of countermeasures. While features such as headlights and brakes are sometimes referred to as active safety, this thesis refers to active safety as systems that can detect safety critical situations and assist drivers and/or VRUs in avoiding or mitigating these situations.

One of the first active safety systems addressing VRU accidents is Night Vision, which has been offered by some vehicle manufacturers since 2000 (Källhammer et al., 2006). Night

Vision systems use infrared technology to detect the presence of VRUs; they aim to improve drivers' view of VRUs in darkness.

Another example of active safety systems addressing car-to-VRU accidents is the recently presented Collision Warning with Full Auto Brake and Pedestrian Detection that is offered by Volvo Car Corporation (Coelingh et al., 2010). Systems like this one detect pedestrians by means of some form of ranging system (laser or radar) in combination with vision cameras; then they estimate the collision risk. If the risk of collision exceeds a certain level, a warning and/or automatic braking are initiated. There are many research projects, either completed or ongoing, in this field both in industry and academia. The European projects PROTECTOR (Gavrila et al., 2001), SAVE-U (Meinecke, 2003), and WATCH-OVER (Meinken et al., 2007) are examples of these. These projects mainly focus on assisting the car drivers to avoid collisions with VRUs, while the corresponding systems that could assist the VRUs have received less attention.

In summary: *A variety of countermeasures, in the fields of traffic engineering and management, education and training of vehicle drivers and VRUs, and vehicle design and engineering, have together contributed to the improved safety of VRUs in recent decades. However, car-to-VRU accidents are still relatively frequent and additional countermeasures are needed. From this it follows that there is an apparent need for active safety systems that can detect safety critical situations and assist drivers and/or VRUs in avoiding or mitigating such situations.*

1.3 The role and principles of active safety systems

Road traffic can be described as a complex cognitive system (Hollnagel and Woods, 2005) which consists of three elements: vehicles, traffic environment, and humans who operate the vehicles, ride in the vehicle as passengers, or take part in the system as pedestrians. These three elements continuously interact with each other and adapt to each other. Sometimes a failure in the adaptation process occurs which can lead to an accident.

Such adaptation failures can be caused by a variety of interacting factors. These factors may include, for example, inaccurate estimation of the point at which loss of control occurs, overestimation of one's own or the vehicle's action capabilities, misunderstanding of how a situation will develop, or a fast change in the demands of driving.

The role of active safety systems is to provide functions that support road users and vehicles to successfully adapt to the changes in the traffic environment (Saad et al., 2004; Ljung Aust and Engström, 2011).

Due to the complexity of the traffic system, the adaptation may be affected at any level of the system. Consequently, the active safety systems can be designed to provide support to the drivers or other road users in any way which addresses one or more of the mechanisms behind the adaptation failures.

Carsten and Nilsson (2001) distinguish four broad categories of active safety systems designed to assist drivers at various levels of a driving task:

- Information providing,
- Warning or feedback providing,
- Intervention with the driver in the loop, and
- Intervention without the driver in the loop.

The information providing active safety systems, also known as in-vehicle information systems, typically help drivers to navigate and inform them about the road conditions, traffic environment, and vehicle state (Carsten and Nilsson, 2001). The variety of navigation systems available on the market today are examples of this category.

For systems that provide warnings, two types can be distinguished: imminent crash warning (ICW) and cautionary crash warning (CCW) systems, see Campbell et al. (2007). The ICWs are generally used in situations where immediate corrective action by the driver (such as braking or steering) is required. The CCW systems are viewed as useful in situations where immediate attention and possible corrective action by the driver is required. Systems providing functions such as forward collision warning, lane departure warning, and drowsiness warning belong to this category.

The third category, intervention with the driver in the loop, includes systems that intervene in the driver's control of the vehicle. These systems are designed in a way that allows the driver to overrule system actions.

A system in the fourth category of active safety systems completely relieves a driver from control over the vehicle. Such systems are typically activated in situations when an action by the driver cannot be expected to contribute to accident prevention. An illustration of typical deployment points of the active safety systems is shown in Figure 2.

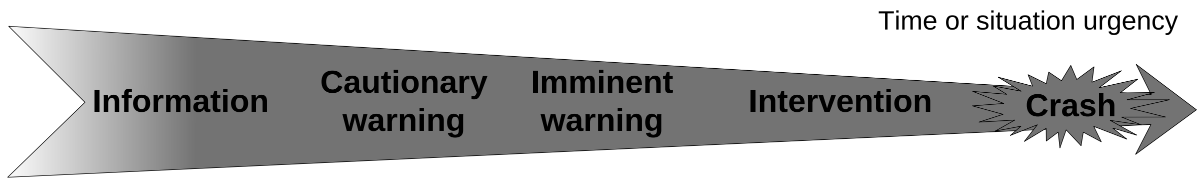

Figure 2. A schematic view of the deployment point for different types of active safety systems in relation to time to collision (or situation urgency).

1.3.1 System design

An active safety system typically consists of three sub-systems or layers (Figure 3); perception, decision, and action (Schulze et al., 2006). The first sub-system covers detection of the driving circumstances and context. It includes various processes for detection and classification of information related to the traffic environment, vehicles, and drivers (e.g., position, speed, direction, type, environmental conditions), Rendon-Velez et al. (2009). Typically, sensor data fusion is carried out at this stage to derive relevant and robust information.

The information obtained by this sub-system is used by the decision sub-system, where the driving situation and conditions are analyzed (situation assessment) in order to identify threats and estimate the risk of a collision (risk assessment), Figure 3. Based on this analysis and the risk level estimated, a decision on an appropriate action and timing of this action is made, e.g., to warn the driver of an impending collision with a VRU if there is enough time for him/her to react to this warning, or to apply the brakes if the time to collision does not allow driver reaction. Depending on the type of action, the requirements for false alarm rate may differ. For example, if a warning system issues a false warning, it may be irritating for the drivers and result in ignoring the warnings, while a false initiation of brakes by an autonomous system may have more serious consequences. Given that safety critical situations involving VRUs often occur in complex traffic environments and that VRU behavior is very dynamic, identifying threats and estimating collision risk in such situations is a challenge for the designers of active safety systems (Gandhi and Trivedi, 2007).

The action sub-system provides information and warnings to the drivers via an appropriate human-machine interface (HMI) and/or executes corrective actions, such as automatic braking and steering, depending on the level of risk. The warnings can be also directed to the VRUs.

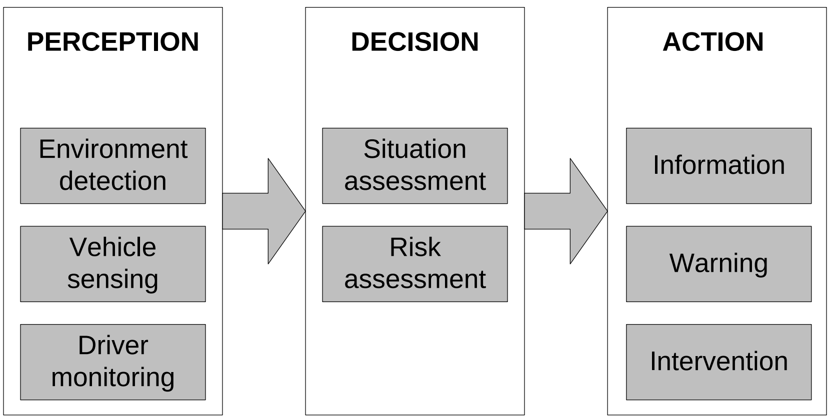

Figure 3. Different sub-systems in an active safety system. Inspired by Schulze et al. (2006).

1.3.2 System configuration

Active safety systems can be configured in different ways; vehicle-based (Coelingh et al., 2010; De Nicolao et al., 2007; Gavrila et al., 2001), infrastructure-based (Hakkert et al., 2002; Lindkvist and Landerfors, 2008; van Houten and Malenfant, 2001), or cooperative (Akazawa et al., 1999; Anund et al., 2010; Aycard et al., 2006; Chan and Bu, 2006; Meinken et al., 2007; Sugimoto et al., 2008).

Vehicle-based active safety systems typically use only information generated by onboard sensors and warn the drivers by means of a HMI in the vehicle, or deploy automatic braking or steering. Infrastructure-based systems, on the other hand, use sensors and HMIs positioned in the infrastructure (Figure 2). Vehicle-based sensors are helpful in detecting VRUs on the road (Gandhi and Trivedi, 2007). However, in environments where “blind spots” are common, these sensors may not fully detect all VRUs at risk. Infrastructure-based active safety systems have relatively high ability to deal with the blind spots, but they can only gather limited information about the vehicles and drivers approaching the intersection. Furthermore, such systems may face difficulties in providing effective warnings to drivers; a warning displayed in the infrastructure may be difficult for drivers to perceive, especially by those who have low situational awareness. Despite the disadvantages, such systems may, for example, be useful for bus drivers at designated bus stops with large concentration of pedestrians (Gandhi and Trivedi, 2007).

Figure 4. An example of an infrastructure-based active safety system. A road sign is equipped with a light-emmitting device that is activated when pedestrians are in the vicinity of the zebra crossing. Courtesy of Amparo Solutions AB.

Cooperative approaches utilize wireless communication technologies to exchange information between road users and/or infrastructure. For instance, Akazawa et al. (1999) suggested a system based on the idea that pedestrians should carry integrated circuit cards able to communicate with a module situated in the infrastructure. If needed, the module controls the traffic lights or issues a warning to the drivers via an in-vehicle HMI. A similar approach is described by Anund et al. (2010) and Meinken et al. (2007). Sugimoto et al. (2008) proposed a system in which the positioning of pedestrians and cars is done by means of a standard global positioning system (GPS) integrated in cell-phones and car navigation systems, respectively. Their system issues warnings to both drivers and pedestrians. Aycard et al. (2006) proposed a system that aims to prevent bus-to-pedestrian accidents in urban intersections and at bus stops. They applied vision-based cameras in the infrastructure to obtain pedestrian data. The bus related data are obtained by means of onboard speed sensors and GPS. The level and direction of risk are presented to the bus drivers via an in-vehicle HMI. Chan and Bu (2006) also presented a system to prevent bus-to-pedestrian accidents. They used an infrastructure based microwave detector and radar for detection of pedestrians and buses, respectively. The collision risk assessment for this is carried out in the infrastructure, and the driver is warned by means of an HMI in the infrastructure or in the bus.

In summary: *There are several categories and configurations of active safety systems. Each of them has its own advantages and disadvantages. Which of them is developed depends on what causation mechanisms are identified in a particular situation. For example, if an unexpected event, such as the sudden appearance of a VRU on the road, is viewed as a key mechanism that can cause loss of control, a system that informs and warns the driver in time about the upcoming event may be suitable. To gain benefit and user acceptance, active safety systems must be designed in a way that will keep the number of unnecessary alarms low.*

1.4 Design process for active safety systems

The design process for safety systems in the automotive industry is commonly described by a “V” cycle (Scholliers et al., 2007). As Figure 5 shows, such a process starts with a definition of functional requirements. These requirements are used as the basis for other steps in the design process. In particular, technical requirements are derived in relation to the functional requirements. The functional requirements are also the basis for the evaluation process, both at the component level (verification) and functional level (validation). As described by Ljung Aust and Engström (2011), hypotheses about the intended effect of a function on road user behavior should be generated from functional requirements, i.e. these allow the evaluator to understand what the system is supposed to do and how it works. Consequently, an incorrect, or incomplete, specification of functional requirements may result in a system incapable of addressing situation for which it is intended, or in an evaluation process, unable to investigate the system performance in an appropriate way.

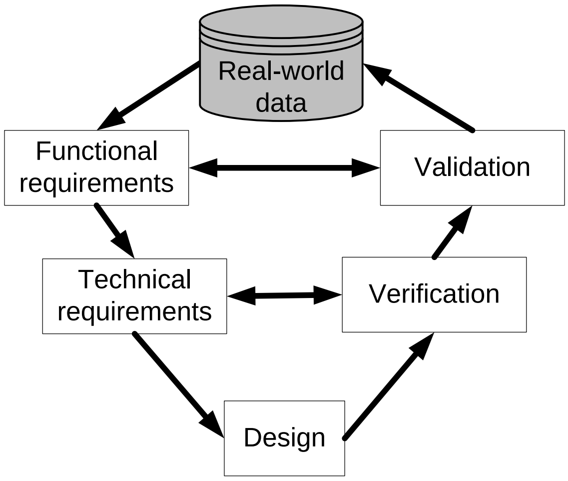

Figure 5. Development process of active safety systems. Inspired by Scholliers et al. (2007).

The first step in the derivation of functional requirements of an active safety system involves a detailed description of the problem that the function is intended to address (Scholliers et al., 2007). Usually, this means that a crash scenario is specified in terms of a flow of events in the traffic, related to at least one road user, at least one vehicle, and a traffic environment. A prerequisite for such a specification is a detailed characterization of the sequence of events which lead to the safety-critical traffic situation that is to be prevented by means of active safety systems (Ljung Aust and Engström, 2011). It is essential that this characterization include information on causation mechanisms and the relationships between them.

The second step in the specification process of functional requirements defines a “use case” based on the crash scenario. This incorporates a description of how an active safety function addresses the sequence of events that lead to the safety-critical situation. First, a general description of the desired functions of the system is provided. For example, a general description for a lane departure warning (LDW) system could be *Providing driving feedback to the driver in lane drift situations* (Scholliers et al., 2007). Second, the expected benefit of the system and the driver behavior are included. This clarifies the circumstances in traffic that the function should address and how it will affect the road user’s behavior and ability to cope with the given traffic situation. Also, a description of the interaction of the function with the road user is described, e.g., auditory warning in the car. Next, information on the time schedule for providing warnings, interventions, or both, is specified. This schedule needs to be detailed enough to provide a basis for time and distance assessment during verification at the technical level (for example, what sensors are needed, how long before the dangerous event the decision has to be made, and when action is required). In addition, requirements related to the dependability of the function (e.g., fault tolerance and reliability) and operational conditions (e.g., weather, light) are derived.

From this it can be concluded that a detailed description of crash causation mechanisms is crucial for the development of active safety systems. Traditionally, crash data have been investigated to accommodate this description, i.e. to explain why and how accidents occur. However, given that accidents are rare in relation to the number of hours spent in traffic every day, it is difficult to obtain a large sample of accidents, especially if the collection is limited to a certain area or road user group. To increase the data sample, several authors have suggested conflicts (incidents) as a surrogate to crashes (see Hydén, 1987). Their suggestion is based on the fact that both crashes and incidents represent a breakdown in situation control and that the mechanisms underlying these are similar and should be addressed by safety countermeasures. Studying conflicts for safety purposes has a long tradition in aviation and other fields of industry, but it has not yet been completely adapted to the domain of active safety systems. Also, studying "normal" interactions in the traffic system can provide information useful for the recognition of safety critical situations. The relationship between the number of normal and various safety critical situations is illustrated in Figure 6, where the most serious ones are at the top of the pyramid (Hydén, 1987).

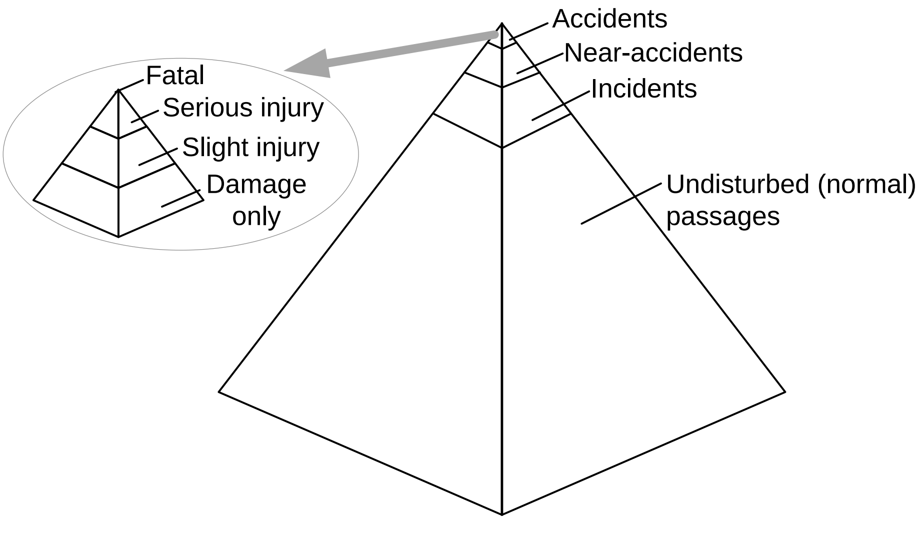

Figure 6. Distribution of normal interactions in the traffic system and those that result in various safety critical situations. Inspired by Hydén (1987).

In summary: *To develop an efficient active safety system, the requirements for the various parts of such a system should be derived on the basis of the real issues that road users encounter in traffic. This requires a thorough understanding of why and how safety-critical situations (incidents and accidents) occur as well as how road users normally interact in traffic.*

1.5 Real-world data sources for derivation of functional requirements

There are several types of real-world data that can be used for the development of active safety systems. Typically, data from crashes are used. Given that there are well-recognized problems with such data (some of which are mentioned in Section 1.4), the observation of conflicts and normal interactions between road users in naturalistic settings, here referred to as naturalistic observation, has been advocated as an alternative, or complementary, approach. Each of these real-world data sources is described in the following sections.

1.5.1 Traditional crash data sources

Two types of crash data are generally available, see Table 2. One is macroscopic data (OECD, 1988), usually consisting of police-reported crashes. The other is microscopic data (OECD, 1988), normally in the form of in-depth accident investigations.

Macroscopic data can often provide statistically representative information on context variables, which is useful in analysis on a general level, e.g., comparison of car types. It is also useful for demonstrating trends over the years as time series, or to define goals to be achieved in the future. This type of data orginates from sources such as police reports, hospitals, and insurance companies. A major disadvantage of such data is that it is difficult to attribute crashes to the factors that have contributed to them since police reports are usually skewed towrads the attribution of responsibility. However, statistical crash data can still be used in a restricted way when it comes to the design of active safety systems. In addition, data from statistical databases usually include cases of specific severity; for this reason, sampling a sufficient number of cases needed to address a specific question requires long sampling periods.

Microscopic data, while rarely statistically representative, can often provide rich information on factors contributing to the collision (Larsen, 2004). These data, which originate from in-depth investigation of road crashes, have been collected for several decades (Baker, 1960; OECD, 1988). Typically, a multidisciplinary team visits the crash scene shortly after the collision (or within a few days) and collects information related to the vehicles and road users involved as well as the traffic environment in which the accident occurred. An important part of the data collection process are interviews with the road users involved and eyewitnesses; this way information about events that led to the accident can be obtained. While the literature surveyed reveals that in-depth investigations have often been considered to be excessive compared with the results obtained (Grayson and Hakkert, 1987), in recent decades, this approach has re-gained attention in the automotive industry. This is mainly due to the usefulness of these data for applications such as crash prevention. Microscopic data can be used to generate patterns of contributing factors and of interactions between these factors, which can be called causation charts (Ljung et al., 2007; Sandin, 2008). To enable the identification of recurrent factors and interactions, these causation charts must be aggregated (Sandin, 2008). This constitutes a challenge, especially when it comes to VRU accidents, due to current lack of databases containing microscopic data and analytical methods for such data (Molinero et al., 2008). Although not very common, there are some in-depth databases around the world containing data from car-to-VRU crashes, e.g., national in-depth accident databases in Germany (GIDAS) and the UK (CCIS and OTS). SafetyNet database is an example of an in-depth database at the EU level.

Macroscopic and microscopic data, both of which have advantages and disadvantages related to the type of information and representativeness, should preferably be combined to allow successful definition of requirements for active safety systems (Fleury and Brenac, 2001). Unfortunately, this introduces difficulty since there are few useful methods available to systematically combine the information from these two sources (Fleury and Brenac, 2001; Ljung Aust, 2010). One of the methods available is based on context-matching idea: first, an accident type is selected based on the context variables available in a macroscopic database, and then, in-depth information is collected for the accidents that occur in a similar context to explain the causation of these. Another method is based on the idea that accidents available in a microscopic database can be grouped according to the context variables and causation mechanisms to form prototypical scenarios (Fleury and Brenac, 2001). The major weakness of these methods is related to the fact that it is difficult to know if the in-depth data represent odd accidents. Ljung Aust (2010) suggested a method, similar to the context matching approach, where data from mail-surveys reported by the road users involved in accidents were successfully used to verify that the in-depth accidents matching the context variables are representative. This thesis applies the context matching approach because data from mail-surveys related to VRU accidents were not available.

Table 2. Various types of accident data and examples of databases containing information about car-to-VRU accidents.

Level of detail	Description	Exampels
Macroscopic	Contain context variables such as road user type, vehicle type, weather conditions, and road conditions that are used mainly for monitoring trends, identifying priorities, and making strategic decisions.	• National statistics of traffic accidents, e.g., Swedish crash database STRADA • CARE database at the EU level
	Contain context variables and description the situation that may include information useful for causation analysis.	• Qualified police reports • Self-reports by road users involved in crashes, e.g., mail surveys • Insurance reports
Microscopic	Contain data from in-depth multidisciplinary investigations with a high number of variables. The aim is to identify causation mechanisms useful for developing countermeasures to prevent recurrence of similar traffic situations.	• CCIS in the UK • GIDAS in Germany • SafetyNet at EU level

1.5.2 Naturalistic observation

An alternative approach to studies of accidents involves the use of naturalistic observation, i.e. direct observation of events as they occur in natural settings. Examples of studies utilizing such an approach include those based on the traffic conflict technique (TCT), (Lord, 1996; Hydén, 1987; Svensson, 1998). These involve observing and evaluating the frequency and severity of traffic conflicts at a given location, typically at an intersection, by a team of trained observers. To date, automated systems are used and these include video cameras as well as other sensors and techniques to extract relevant information from the site-based recordings (Laureshyn et al., 2008; Steffen and Seyfried, 2010). Although this approach to collecting data has advantages, its major disadvantage is that data collection systems used are stationary, i.e. the data are collected from pre-defined locations. While such data can provide information that is useful for infrastructure improvements, it does not provide detailed information about driver behavior, which is needed for the development of active safety systems (Christoph et al., 2010).

Another type of study involving naturalistic observation of driver and VRU behavior uses vehicles, often referred to as experimental or instrumented vehicles, equipped with cameras and other sensors for driver, traffic environment and vehicle monitoring (Schmidt and Farber, 2009). Sometimes, sensors are carried by the VRUs (Geruschat et al., 2003; Walker, 2007). Studies of this type are useful for understanding road user behaviors that cannot be studied based on data from interviews with road users or simulator experiments, for example. Their disadvantages, however, are that: (a) the participants are often explicitly recruited for a given research, (b) the participants are typically provided with some instructions (e.g., pass a given intersection), and (c) the observers are usually in the vicinity of the participants (e.g., sitting in the passenger seat or standing on the sidewalk). Taken together, these facts preclude the possibility of observing some behaviors, important for the development of active safety systems, that may be likely to occur in ordinary traffic conditions (Sagberg et al., 2011).

Recent advances in technology have enabled extensive observation studies in more naturalistic settings, commonly referred to as naturalistic driving (ND) studies (Dingus et al., 2006). The methodology generally involves observing drivers who use their own vehicles on a day-to-day basis. The vehicles are commonly instrumented with relatively unobtrusive sensors, including video cameras, to record information related to road user behaviors as well as vehicles and road environment. Typically, the data collection is carried out under longer time periods (e.g., several months) and is event based, i.e. the data collection is activated only when a critical event occurs (e.g., when the deceleration exceeds a certain level). There are, however, studies that collect the data on more continuous bases. Such studies are especially valuable since they enable the analysis of both normal and safety-critical traffic situations. A branch of the ND collection is referred to as field operational tests or trials (FOTs). In FOTs, the vehicles are instrumented with safety systems; the primary goal of the data collection is to evaluate these systems and driver interactions with them (Sagberg et al., 2011). A possible limitation of the ND studies (and FOTs) is that the drivers may be aware of the fact that they are being observed and behave in a way that differs from their ordinary behavior. There are, however, studies that indicate that drivers tend to forget about being observed (Dingus et al., 2006). A great majority of the ND studies and FOTs involves passenger cars, trucks, and buses. However, there are some recent attempts to conduct ND studies involving motorcycles. Some completed or ongoing ND studies and FOTs include:

- Distractions in everyday driving (Stutts et al., 2003);
- 100-Car naturalistic driving study (Dingus et al., 2006);
- Test site Sweden FOT (SAFER, 2008);
- Sweden-Michigan naturalistic operational test (SeMiFOT) (Victor et al., 2010);
- Distraction in commercial trucks and buses (Hickman et al., 2010);

- 2-wheeler behaviour and safety (2BESAFE) (Spyropoulou et al., 2010)
- The first large-scale European FOT on active safety systems (euroFOT) (Benmimoun et al., 2011); and
- The second strategic highway research program (SHRP 2) (Antin et al., 2011).

The goal of all of these data collections, except for Dingus et al. (2006), was to explore research questions related to driver behavior, driver distraction, performance and the effects of using the system, usually in relation to the traffic situations involving motorized vehicles (Sagberg et al., 2011; McLaughlin et al., 2009). Dingus et al. (2006) analyzed driver behavior in 108 incidents involving pedestrians. From this it follows that the research questions related to road user behavior in safety-critical situations involving VRUs have received only limited attention. This is mostly due to the lack of methods that can automatically extract information about VRU behavior from sensor data. The data used in this thesis include parameters related to pedestrian behavior as well.

In summary: *Understanding of causation mechanisms underlying a given accident type has traditionally been sought through the analysis of data from in-depth accident investigations and reports from institutions such as the police, insurance companies, and hospitals. Recent developments in technology have enabled the collection of large amounts of data from various situations in traffic. The goal of such data is mainly related to driver behavior in situations involving motorized vehicles, while situations involving VRUs have received limited attention.*

1.6 Methods for analysis of real-world traffic data

To be truly useful for the development of active safety systems, real-world traffic data must be analyzed in an appropriate way, i.e. applying methods that are likely to reveal relevant information. In this section, methods that are typically used for the analysis of microscopic (in-depth) and macroscopic (police-reported) accident data are outlined. It should be noted that the goal is not to give a general review of all existing methods.

1.6.1 Analyzing macroscopic accident data

Police reported data can be analyzed by applying simple statistical methods for the estimation of frequency and rate (Kweon, 2011). Frequency analysis is typically performed by counting the occurrence of a certain parameter, or parameters, registered in the macroscopic databases. A rate is obtained by dividing the frequency by a normalizing factor (known as exposure measure). Examples of normalizing factors include population, the number of vehicles passing a given location, and the numbers of registered drivers and vehicles. These are not usually registered in macroscopic accident databases; they must be obtained from other data sources such as a state highway agency. Another way of analyzing general parameters is by applying various types of regression models (Kweon, 2011). Such models include discrete response models (e.g., binary logit, ordered probit) and count data models (Poisson and negative binomial models).

1.6.2 Analyzing microscopic accident data

In safety-critical industrial domains, various methods have been developed and used to analyze incident and accident causation. Examples of such methods include: events and causal factors charting (ECFC); barrier analysis; root cause analysis; fault tree analysis; systematic cause analysis technique (SCAT); sequential timed events plotting (STEP); man-technology-organization analysis (MTO); TRIPOD; systems-theoretic accident model and process (STAMP); and cognitive reliability and error analysis method (CREAM). For more details on these methods see, Qureshi (2007), Sandin (2008), and Sklet (2002).

A major difference between these methods lies in the accident model(s) on which they are based. Generally, accident models provide a high-level explanation of why accidents occur, including the relation between causes and effects. Such models can be divided into three broad categories: simple linear (sequential), complex linear (epidemiologic), and systemic (Qureshi, 2007).

The first two types of models are similar in that they view accidents as a sequence of failure events that occur on the component level in a socio-technical system. They differ, however, in the number of such sequences. In simple linear models, accidents are regarded as a result of a single sequence of component failures that occur in a specific temporal order, while complex linear models include relationships between interdependent components (Qureshi, 2007).

Systemic models view accidents as a complex and interconnected network of events that occur on the level of a socio-technical system as a whole. More specifically, a socio-technical system is considered as a dynamic multi-process that is continuously adapting to achieve its goals. Consequently, accidents are regarded as an adaptation failure of one or more of the processes used to achieve these goals. This modeling approach is especially suitable for the development of countermeasures that aim to prevent similar accidents from occurring.

Each of these model categories (and the methods based on them) has its own advantages and disadvantages, depending on the type of application. As for the causation analysis of incidents and accidents in road traffic, several researchers have concluded that it is a complex socio-technical system (Huang, 2005; Larsson et al., 2010). Accordingly, they have concluded that linear modeling approaches are not able to capture the complexity of causation in road traffic accidents; analyzing causation in road traffic accidents requires a systemic modeling approach. The methods used in this thesis for causation analysis of the safety-critical traffic situations are based on such an approach.

Although the number of systemic methods, reported in the literature, which have been used for the causation analysis of road accidents is limited, some examples do exist. Accident causation analysis with seven steps (ACASS) (Otte et al., 2009), human functional failure (HFF) (van Elslande and Fouquet, 2007), and the driving reliability error analysis method (DREAM) (Ljung, 2002) are examples of systemic-based methods that have been developed specifically for the causation analysis of road accidents. Each of these methods has its own advantages and disadvantages, depending on the goal of the analysis.

A comparison of ACASS and DREAM, carried out in the European project SafetyNet (Björkman et al., 2008), showed that similar causation factors could be identified with these two methods. The major difference between ACASS, HFF, and DREAM is that the first two methods do not facilitate the identification of causal relationships between factors. On the other hand, DREAM provides a link system that enables a systematic, graphical illustration of such relationships. Although such an illustration may seem complex at a first glance, it is a useful tool when it comes to the aggregation of several accidents. Mainly, DREAM has been used for the analysis of causation in single and multiple vehicle accidents. In SafetyNet it was applied for the first time to car-to-VRU accidents. A literature review revealed that the applicability of DREAM to the causation analysis of road traffic incidents is still unexplored.

1.6.3 Analyzing naturalistic observations

Methods for the analysis of real-world traffic data from naturalistic observations vary largely depending on the research questions. Typically, these data are used to investigate interactions between elements in the traffic system in terms of measures such as time-to-collision and post encroachment time. The topic of driver attention allocation is one of the major topics addressed by analyzing data from naturalistic observation. Furthermore, depending on the size of the data sample, various statistical approaches (as exemplified in Section 1.6.2) can be applied to analyze the frequencies of contextual and behavioral variables and correlations between them, for example. For the analysis of causation based on such data, methods for the analysis of accident causation (Section 1.6.1) can probably be used. However, it should be noted that the literature surveyed does not show that the applicability of such methods has been explored for this purpose.

In summary: *Utilizing real-world data in the development process of active safety systems requires appropriate methods for the analysis of these data. Given that traffic is a complex and dynamic system, methods able to capture accident causation should be based on a systemic model. There is a very limited number of such methods, and their applicability in accidents and incidents involving VRUs is virtually unexplored.*

1.7 Aims

The overall aim of the present thesis is to explore diverse types of real world data sources in order to gain knowledge useful for the development and evaluation of active safety systems to prevent passenger car-to-vulnerable road user (VRU) accidents. To this end, the following specific aims are defined:

- To assess whether a combined analysis of in-depth and police reported crash data yields information on driver behavior and contextual variables that is relevant for the development of active safety systems (Paper I);
- To explore whether an analysis of in-depth crash data provides information about VRU behavior and contextual variables that is relevant for the development of active safety systems (Paper II);
- To develop a methodology for the analysis of incident causation data that is based on video recordings from naturalistic driving studies; in addition, to determine whether such an analysis yields information on driver behavior and contextual variables useful for the development of active safety systems when applied to car-to-pedestrian incidents (Paper III); and
- To develop an approach for the analysis of pedestrian behavior based on data collected in a naturalistic driving study; in addition, to find out if this approach reveals information useful for the development of active safety systems (Paper IV).

2 Summary of appended papers

2.1 Paper I

Title: Requirements of a System to Reduce Car-to-Vulnerable Road User Accidents in Urban Intersections

Background

Advanced driver assistance systems (ADAS) can prevent, or mitigate, accidents by supporting drivers in their primary driving task. To inform the design of such systems, it is necessary to comprehend the underlying contributing factors and the context in which the accidents occur.

Aim

One aim is to identify contributing factors and drivers' support needs in passenger car-to-vulnerable road user (VRU) accidents in urban intersections. Another is to identify the most promising ADAS type and to derive preliminary functional requirements for such a system.

Method

The study is based on macroscopic and microscopic accident data analysis and findings from the literature. The microscopic data consisted of causation charts describing contributing factors for 60 accidents in X and T shaped intersections. The charts have been compiled by means of the SafetyNet Accident Causation System (SNACS). One chart for each road user was obtained. In this study, only the individual charts for the drivers were aggregated. The drivers' support needs were identified by analyzing the frequency of the contributing factors. The macroscopic data were obtained from the Swedish national accident database, STRADA. It covered a time period of five years and consisted of context parameters from 9702 accidents. The data from the literature consisted mainly of information that was unobtainable from the accident data analysis, such as driver reaction time and car speed.

Results

The accidents analyzed were attributed mostly to insufficient timing of actions and distance misjudgments. The most recurrent contributing factor was failure to observe the VRUs. This was mostly due to physical and environmental obstructions, perceptual errors, and/or lack of information. An ADAS should therefore help the drivers to notice the VRUs and enhance their ability to interpret the probable development of events in the near future. It should include a combination of imminent and cautionary collision warnings, with additional support in the form of information about intersection geometry and traffic regulations. These should preferably be deployed in-vehicle and according to the likelihood of accident risk. It may be necessary to predict road user intentions approximately 3.2 seconds ahead. The ADAS must be able to operate under a variety of road, weather, and light conditions. It should have the capacity to support drivers when their view is obstructed. To this end, it is recommended that onboard sensors should be complemented by cooperative infrastructure-car systems.

Discussion

The functional requirements were derived from a limited number of cases. To verify the generality of the results obtained, a complementary approach would be needed. Furthermore, the accidents were grouped according to context variables. However, it would be valuable to investigate the driver needs depending on the car and VRU trajectories and how they affect the functional requirements specified. The study also highlights a great need for a method that can systematically “transform” the information from the aggregated SNACS charts into requirements.

2.2 Paper II

Title: Causation mechanisms in car-to-vulnerable road user crashes: Implications for active safety systems

Background

To inform the design of active safety systems, it is necessary to comprehend the underlying contributing factors and the context in which the accidents occur. Each road user involved in a crash has failed to adapt, for one or more reasons, to the development of events leading to the crash. The development of active safety systems can therefore benefit from an analysis of VRU behavior in car-to-VRU crashes.

Aim

One aim is to acquire a deeper understanding of why VRUs become involved in crashes with cars, i.e. to identify crash causation patterns from a VRU perspective. Another one is to investigate the implications of these patterns for the development of active safety systems. The implications are explored from two points of view: those for the active safety systems that aim to assist the VRUs, and those for the active safety systems that aim to assist the car drivers.

Method

Causation charts for 56 VRUs involved in intersection crashes with cars were analyzed. These charts were compiled in the European project SafetyNet using the SafetyNet Accident Causation System (SNACS). One chart for each road user was obtained. In this study, only the individual charts for the VRUs were aggregated. The VRUs’ support needs, as well as the implications for active safety systems that aim to assist the car drivers, were identified by analyzing the frequency of the contributing factors.

Results

About 70% of the 56 VRUs misunderstood the low speed of the car, expected that the driver would slow down, misjudged the gap in the traffic, suddenly changed their own behavior, underestimated own conspicuity, or could not perceive a sudden action by the car driver. In addition, 30% of the 56 VRUs did not see the car, mainly due to obstructions in the environment. From this it follows that designers of active safety systems cannot expect the VRUs to interpret the situation correctly, even when they have a free line of sight. Many VRUs would benefit from a system to help them understand whether a driver intends to slow down and if a driver is slowing down to let them cross. Also, a system informing the VRUs about the traffic gap size or a system that makes the car speed more uniform may be useful. To address sudden changes in the VRU behavior and issues related to their conspicuity, autonomous and night vision functions may be needed. One can also foresee that various cooperative systems could be important to address obstruction issues.

Discussion

A direct comparison of the results obtained here and in other studies is difficult to make due to the differences in methods of data analysis and the limited number of cases. However, a brief literature review showed that many of the findings are in line with previous researches. There are also some deviations from the previous research, which should be investigated in future studies.

2.3 Paper III

Title: Driver behavior in car-to-pedestrian incidents: An application of the Driving Reliability and Error Analysis Method (DREAM)

Background

Naturalistic driving studies including video-recordings provide detailed information on events and circumstances prior to safety critical situations, such as incidents, near-crashes, and crashes. This information is difficult to obtain from traditional crash investigations. An in-depth understanding of causation in critical situations is necessary for developing safety countermeasures that aim to prevent these situations.

Aim

One objective is to investigate what type of information can be obtained from incident causation charts derived by means of the modified DREAM. Another objective is to ascertain whether this information can inform the design of Advanced Driver Assistance Systems (ADAS).

Method

Causation in 90 video-recorded car-to-pedestrian incidents from the driver perspective was analyzed. The data were collected in a naturalistic driving study in Japan. The Driving Reliability and Error Analysis Method (DREAM) was modified and used to identify the most common causation patterns. The implications for the ADAS development were determined by analyzing the frequency and type of causation factors.

Results

The results show that the majority of the drivers in intersections misunderstood the situation due to visual obstructions and/or allocation of attention towards something other than the conflict pedestrian. Apart from intersections, half of the drivers were involved in incidents where the pedestrians behaved in an unexpected way. Information on HMI design, driver fatigue, vehicle maintenance, and driver experience is unobtainable from the data used. Interactive ADAS functions, such as information and warning, could have averted many intersection incidents. Semi-autonomous functions may be needed to prevent incidents away from intersections. One can also foresee that various cooperative ADAS would be beneficial for timely detection of pedestrians in situations where obstructions are present. The interactive ADAS should redirect the driver attention towards the most critical road user, which puts high demands on the HMI design.

Discussion

Most of the information could be observed directly from the video-recordings, except for driver expectations and cognitive load which had to be interpreted from other cues.

2.4 Paper IV

Title: Predicting the probability that a pedestrian will cross the road

Background

Accurate prediction of pedestrian intent to cross the road or stay on the curb is necessary for the development of active safety systems for prevention of car-to-pedestrian accidents as well as for the evaluation of such systems in automotive simulators. Hence, statistical models able to perform this prediction are essential. In recently developed systems, these models are based in general on the pedestrian’s position and heading in relation to the current path of the car. A basic premise of the proposed research is that predictive models should take into account some additional indicators of pedestrian intent to cross the road, such as pedestrian head orientation prior to entering the road.

Aim

The aim is to explore whether parameters such as pedestrian-to-road distance and head-orientation can improve the prediction of the probability that a pedestrian will cross the road.

Method

The logit models are used to predict the pedestrian probability to cross the road based on the behavior of 102 pedestrians. The coefficients of the model parameters are obtained by means of maximum likelihood estimation. The coefficient performance is assessed through a Wald significance test and log likelihood ratio. Bootstrap sampling was also used to ascertain the variances of the coefficients and the probability. Overall, six parameters were investigated: car speed, car-to-collision distance, pedestrian-to-road distance, pedestrian speed, pedestrian head orientation, and time-to-collision.

Results

The analysis showed that car speed, pedestrian-to-road distance, pedestrian speed, and pedestrian head orientation are significant for the probability function. A model including these parameters showed to have better characteristics than the other models excluding these parameters or combining them with others. The analysis also showed that nobody is likely to cross if the time separation between the car and pedestrian is 2 seconds, or less.

Discussion

Although the bootstrapping demonstrated that the model suggested is rather stable, the model performance should be evaluated based on a larger data sample. Also, future research should investigate why the car-to-collision distance and the time-to-collision seemed to be insignificant.

3 Addendum: An example of a future active safety system

3.1 Aim and outline

The aim of the present addendum is to illustrate an example of how real-world data from various sources can be used in an early development phase of active safety systems.

The active safety system concept presented here was partly developed in the VISAS project[1]. It is important to point out that the system is meant to serve as an experimental framework rather than a complete and final solution. The system is mainly based on general understanding of the VRU accident scenario and is here presented and discussed in relation to the findings from Papers I–II. First, the functional requirements that the system should fulfill are presented. Next, detection, risk assessment, and human-machine interface are described followed by some preliminary evaluation results and discussion.

3.2 Functional requirements

The requirements that the active safety system should fulfill can be summarized as follows:

- The primary aim of the system should be to help drivers to observe the VRUs in time when their view is obstructed by physical objects, such as buildings, other vehicles, and vegetation. This includes enhancing the drivers' ability to interpret the development of events in the near future.
- The system should provide a combination of imminent and cautionary crash warnings, with additional support in the form of information about intersection geometry and traffic regulations where relevant.
- Warnings should preferably be deployed by means of an in-vehicle HMI, according to the likelihood of accident risk. To predict the accident risk accurately, the road users should be tracked over time and their intended path predicted.
- The system should primarily operate under good light and weather conditions. However, to address a wider range of accidents, the system should be able to operate under adverse conditions.

[1] The project VISAS was collaboration between Volvo Car Corporation, Autoliv Electronics AB, and Chalmers University of Technology funded by the Swedish Agency for Innovation Systems (VINNOVA). Habibovic participated in the specification of the requirements for the system (including those for the communication protocol), the selection of the sensors, development of the VRU detection and tracking algorithms, and preliminary evaluation of the system.

In particular, the function concept presented here is intended to provide support to car drivers in urban intersections, where the risk of collision with the VRUs is high and the drivers' view is obstructed by a building or by a vehicle. As visualized in Figure A1, the basic idea of the concept is to use sensors positioned in the infrastructure for the detection of VRUs. The safety related VRU data is continuously broadcast to the cars in the vicinity. The cars use onboard sensors to obtain their own position and velocity. By using these data along with a digital map of the intersection, each car's system estimates its own collision risk with the VRUs detected. If the risk estimated exceeds a specific threshold, a warning is issued to the driver. Together with the warning, information about the intersection outline and traffic regulation is displayed. Hence, the system provides cautionary warnings rather than imminent warnings; it prepares the car driver for a possibly dangerous situation. The system includes five key subsystems:

- detection of the VRUs and estimation of their position and velocity,
- recording of car position and velocity,
- infrastructure-to-vehicle (I2V) communication,
- accident risk assessment, and
- human-machine interface (HMI).

Each of these subsystems is presented below.

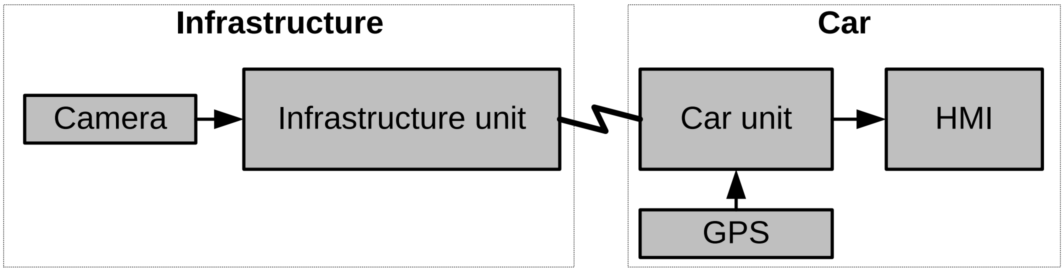

Figure A1. Conceptual scheme of the safety system suggested. The VRU detection and tracking are performed in the infrastructure. The infrastructure and car units wirelessly communicate with each other. The accident risk assessment is made in the car unit. A digital map of the intersection is implemented in this unit. In the future, such a map is expected to be in the infrastructure unit instead. The information and warnings are displayed via an in-vehicle HMI.

3.3 Detection and tracking of the VRUs

The system concept developed uses a camera (IQEye 853) operating in the visible spectral range to detect the VRUs. The camera has a bird's-eye view of the intersection. The images are transferred to the infrastructure unit in which the image processing is carried out in four steps: object extraction, classification, positioning, and tracking.

In the first step, the object extraction is performed by segmenting the foreground and background pixels in the images. For this, a continuously updated background model of the scene is utilized. The segmentation results in connected regions of the pixels (blobs). In the next step, blobs are classified as object types by using a Bayesian network classifier that was trained on a sample of real-world data from a variety of scenarios for which the ground truth classification was made manually. In the third step, the position coordinates of a blob in the image plane are obtained by finding the center of its area. These coordinates are then mapped on the ground plane and WGS84 coordinates by using a digital map of the scene. This mapping is possible because the camera is stationary, and its position and distance to the stationary objects in the scene are known. A basic assumption here is that the ground plane, which corresponds to the road surface, is planar; this is not correct since roads are usually constructed with a grade to facilitate drainage. However, the assumption is thought to be sufficient since the grade is insignificant when compared with the height of the camera. Finally, each blob is tracked by using a probability matrix mapping of a detected blob with previously detected blobs. Selected features of the blobs (e.g., height, width, color) are taken into account and the best match is chosen. The fact that the VRUs are sometimes occluded by moving or stationary objects in the traffic environment can cause a single object to be viewed as several blobs, or multiple objects to be viewed as a single blob. To handle such situations, several rules are formulated. For instance, if a blob is not associated with any blobs in the previous image, a temporary identity number (ID) for that blob is generated; the ID becomes definite only if it has appeared in a certain number of consecutive frames.

The data available from the video data processing software include object type (such as pedestrian, bicyclist, and car) as well as height, width, color, and structure information. In addition, object position, speed and traveling direction in a two-dimensional map of the scene and WGS84 coordinates are given.

3.4 Car position and velocity

To estimate the collision risk between a car and VRUs, the car position and velocity are needed. The present study integrated a standard GPS in the car unit to provide these data. To compensate for possible inaccuracies in the GPS measurements, a simple algorithm similar to the one described by Huang and Miller (2004) was used. The algorithm utilizes a digital map of the intersection and its vicinity to "match" the lateral position of the car to a given road segment.

3.5 Infrastructure-to-vehicle communication

The wireless communication between the infrastructure and car unit (I2V) provides the car unit with data characterizing the VRUs. The key requirements for the I2V are therefore a low latency, high reliability, and high throughput. The present study implemented commercial off-the-shelf IEEE 802.11g wireless networking units in both the infrastructure and car unit. Moreover, it developed a communication protocol, based on the ideas from standardization such as ISO CALM (Williams, 2004) and IEEE WAVE (IEEE, 2008). The protocol consists of three parts: the infrastructure server broadcast, the car request, and the infrastructure server transfer. The infrastructure communication unit regularly broadcasts a list of the available services. Currently, the only available service is the VRU data. In the future, a digital map, traffic information, and similar services may be included. The list received is analyzed for relevance by the car unit; next, a request for services desired is sent to the infrastructure server, which then triggers the transmission of the desired services to the car.

3.6 Accident risk assessment

The ideas that are used for estimation of the accident risk are adopted from the car safety systems proposed by Miller and Huang (2002) and Huang and Miller (2004). Given the current position and velocity of the car and VRU, their future trajectories are predicted with the assumption that their velocities will remain constant. If the car and VRU need the same amount of time to reach a point where their trajectories intersect, there is a risk of collision. This point is here referred to as the closest point of approach (CPA), see Figure A2. It is important to note that uncertainties in the velocity and position measurements are also taken into the consideration. A warning is issued if the difference between the car’s distance to the CPA and the distance needed to stop the car is under a predefined threshold for a given time interval. The distance needed to stop the car is estimated taking into account the current velocity, expected deceleration, and driver reaction time.

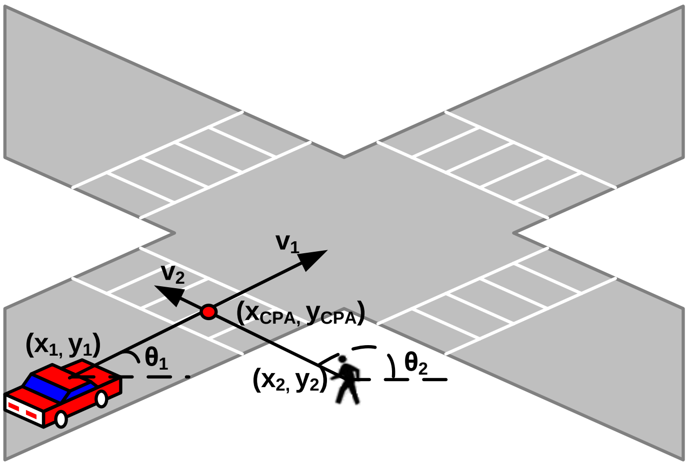

Figure A2. Schematic of how the closest point of approach (CPA) is estimated.

3.7 Human Machine Interface

The system concept presented here used visual and auditory HMIs to provide warnings and information to the drivers. The visual HMIs include a Head-up-Display (HUD), a navigation display (NAVI display), and a blind spot indicator (BLIS). The auditory HMI consists of a single beep tone and a verbal message. It should be noted that these interfaces do not necessarily have to be used simultaneously; they are introduced to show the options available. In the current implementation, it is possible to activate and deactivate the intersection warning function and to select the HMI type.

The HUD consists of devices that project red light on the windshield to attract the driver's attention in a specific direction. Similar, the BLIS, consisting of one lamp on each side of the vehicle, mounted close to the A-pillar, provides a blinking light signal when an accident is at risk to direct the drivers' attention to a specific direction. The NAVI shows the intersection geometry, the highest priority traffic regulation, and the highest priority threat. In Figure A3, the highest priority traffic regulation of is "yield". The highest priority threat is a bicyclist coming from the right. The single beep tone is mainly used to indicate that the visual HMI is activated. Although the tone is easy to notice, it is designed to be non-distracting for the driver. The verbal message is in the form of a human voice. The verbal message is intended as a complement to the visual warnings. For instance, the verbal message that accompanies the warning shown Figure A3, is: "Bicyclist from the right!".

Figure A3. The NAVI display shows a warning that a bicyclist is coming from the right. It also shows that the test vehicle has to yield in the intersection.

3.8 Evaluation of the system proposed

An initial evaluation of the system performance was carried out partly in an intersection and partly in a simulation. The evaluation was made with a limited video data sample and without regular road users present. The camera (12 frames per second and image size of 640 x 480 pixels) was roof mounted on a building adjacent the intersection; about 15 meters above the ground. The camera view is shown in Figure A4. The system was evaluated mainly in a traffic situation where the driver of the test car approached the intersection on Leg I, while one or more pedestrians walked along Leg II and wanted to cross Leg I (Figure A4). As shown, a building obstructed the driver's view of the pedestrian until she was approximately one meter away from Leg I. The evaluation was conducted in daylight and under various weather conditions.

Figure A4. The view from a camera located in the evaluation site.

For the performance evaluation of the detection subsystem (see Section 3.3), it was decided that an acceptable level of position accuracy was obtained when a pedestrian walking, running, or standing still on the sidewalk was also positioned on the sidewalk. For the velocity, an acceptable level of accuracy was achieved when the measurement did not differ more than 5% from the ground truth value. A state-of-the-art video analysis software (Image Systems TrackEye 5.0) was used to obtain the ground truth position and velocity. Also, the pedestrian was allowed to walk along a predefined line on the pavement and this was "manually" compared with the extent to which the measured position values "matched" the line. This also allowed comparison of the average speeds and heading. Overall, the results of the evaluation reveal that the detection is accurate under daylight, dry weather and dry road surface conditions. However, inconsistencies in classification and tracking are observed in situations where several pedestrians are close to each other. Similar problems are also faced when shadows from moving objects are present or when it is raining.

For safety reasons, the evaluation of the collision risk assessment was carried out using simulated GPS data for the car, i.e. the car was standing still but it "appeared" to be moving. The pedestrian data were obtained in real-time. The result of the evaluation show that the I2V communication functions without delays longer than 300 ms. The prediction of a possible collision is accurate provided neither the pedestrian nor the car rapidly change direction or speed.

3.9 Concluding remarks

The present study developed a conceptual safety system that is meant to serve as an experimental framework rather than a complete and final solution. The system functions mainly to support drivers in maintaining the primary driving task in intersection situations associated with accident risk due to permanent obstructions in the traffic environment. Such obstructions were identified as one of the most frequent factors that contributed to the accidents and incidents analyzed in Papers I–II. By utilizing the relevant data from both infrastructure and car based sources, it estimates the accident risk. If the risk is high, an auditory and/or visual warning is issued to the driver via an in-vehicle interface. As a part of the warning, information on the intersection layout and traffic regulations is also given. This system is here referred to as the intersection and car cooperative collision warning system (CCWS). The effects that its technical feasibility and widespread installation would have on the user acceptance and overall safety benefit are discussed here.

Technical feasibility

As the system concept suggested is mainly based on simple, commercially available, and inexpensive technologies, its ability to estimate the collision risk with a high level of accuracy is limited. Hence, it aims to issue cautionary warnings that require a lower level of accuracy than imminent warnings and intervention. The findings in Papers I–II show that both cautionary and imminent warnings may be needed, especially in situations where the driver does not react to a cautionary warning or where the VRU suddenly enters the road. However, the initial evaluation indicated that the number of false warnings may be greater than drivers are willing to accept. It is likely that a significant reduction of the false warnings can be achieved by “moderate” improvements in the quality of (a) car position and velocity, (b) detection and tracking of VRUs, and (c) estimation of the collision risk. In addition, the other subsystems (I2V communication and HMI) could be improved.

The CCWS concept presented here uses a commercially available GPS unit to obtain car data. However, the accuracy and availability of the GPS measurements may be degraded in urban areas due to occlusions such as high buildings, bridges, and trees. To overcome the accuracy problems, an algorithm was introduced which, by utilizing a simple digital map, positions the car in the closest road section. This solution will not provide very accurate car position if the street has more than one lane in a given direction. Moreover, it does not solve problems with the inaccuracies in the longitudinal positioning. This means that it will be necessary to incorporate complementary information sources to address these issues. For instance, solutions such as those suggested by Tan and Huang (2006) and by Rezaei and Sengupta (2007) may be applied. These publications proposed vehicle positioning algorithms for use within systems which employ vehicle-to-vehicle communication. These authors used an extended Kalman filter to fuse the data from a GPS base station with data from in-vehicle sensors, such as yaw rate, wheel speed, steering angle, and acceleration.

The evaluation suggested several potential improvements that could be made to the VRU detection subsystem. One of them involved occlusions of the VRUs by moving and stationary objects. Shadows cast by moving objects intensified occlusion problems and degraded the quality of the target outlines, which in turn affected the segmentation between background and foreground elements. These problems can be alleviated by using multiple cameras to observe the scene from different angles, or by using some additional sensors that do not have the same disadvantages as the vision based cameras.

For the system proposed, the behavior models of VRUs and drivers are conservative, which could cause many false alarms. Incorporating more advanced behavioral models is expected to contribute much to solving this problem. For example, Papers I–II show that the actions by the VRUs are often driven by unjustified expectations about the car drivers’ behavior. However, modeling and predicting such behaviors in advance is a challenge, as the amount of data available from the pre-crash phase is often limited. To overcome this problem, several studies have focused on modeling normal behavior (accident and conflict-free situations) of the VRUs and drivers (Manuszak et al., 2005; Yang et al., 2006), as well their behavior in near-accident situations (Himanen and Kumala, 1988). The behavior deviating from these models is then seen as potentially dangerous. Generating behavioral models for VRUs is especially complex, since they can change their behavior more freely than car drivers. A key issue to address is therefore how the intentions of VRUs to cross a street can be recognized in advance. Such an approach is taken in Paper IV.

In the current system prototype, the information and warnings are presented simultaneously. However, the drivers’ reaction to and interpretation of these was not evaluated. If needed, the settings can easily be changed to issue the information and warnings at different moments in time. In addition, it remains to be evaluated which of the HMIs proposed, or which combination of them, will be the most effective in terms of usability and driver acceptance. Furthermore, the information and warnings to the drivers are issued by utilizing the in-vehicle HMI devices. This way, the HMI can be personalized and adapted to each driver. The manufacturers could also design the HMI to fit their vehicles. On the other hand, displaying information and warnings in the infrastructure may be less obstructive to the drivers. From the literature surveyed, it is not clear which of these approaches would be the most effective in this particular case. Hence, whether the information and warnings should be provided by the infrastructure, vehicles, or both, should be investigated in more detail.

The I2V communication system has worked well. However, it is expected to be replaced by standards such as DSCR and IEEE 802.11p. The map download service is not implemented in this work. Although the map messages can be large, they are not expected to cause delays for the safety related data because the map download (and similar services) should be initiated as soon as the communication between the car and intersection is established. Today, the latency time of the WLAN system used is typically about 300 ms, which is regarded as sufficient for a system providing information and cautionary warnings. However, a shorter latency time may be required for imminent warnings and automatic intervention. The range of communication for such a system, on the other hand, would be shorter. A need for a longer communication range is not anticipated in the future.

Widespread installation needed to improve safety

Widespread installation of the system suggested will greatly affect the acceptance and safety benefit achieved. It is believed that the number of car-to-VRU accidents in intersections will be significantly reduced with the CCWS suggested here only if the number of both cars and intersections equipped with the system is high.

A low number of cars and intersections equipped with the system is not expected to contribute significantly to the improved safety of the VRUs. The probability that an equipped car passes an equipped intersection at the moment when there is a critical situation would be marginal. Moreover, the information and warnings would be issued very infrequently and to a limited number of drivers. Consequently, undesirable behavioral adaptations, such as generalization of behaviors and delegation of responsibility, may occur. For instance, some of the drivers could assume that the system will provide support in all intersections. This, in turn, could result in a disproportionate increase of feeling safe for these drivers. It could also happen that a driver who has two cars, one with the system and the other one without it, expects to be supported even when he/she is using the unequipped car. Similar issues are anticipated if the number of either cars or intersections equipped is low. From the perspective of drivers, it would probably be more useful to have a high number of equipped intersections; a driver having an equipped car could be warned frequently. On the other hand, if it is possible to identify “black spots”, i.e. intersections where accidents and near accident situations are especially frequent, then a greater safety benefit could be expected even for a low number of equipped intersections.

To avoid undesirable behavioral adaptations and at the same time increase the safety of the VRUs in intersections and other locations, the system suggested should be integrated in the future with an onboard VRU safety system. Some of the possible onboard VRU systems already exist in some cars and others will be introduced in the near future. For this, the infrastructure based sensors can be viewed as a complement to the onboard sensors. Based on that, it can be foreseen that a high safety benefit could be achieved with a low number of intersections equipped and a relatively high number of cars equipped. This way, frequent information and warnings could be issued to many drivers in places where the view of onboard sensors is not obstructed, as well as in some high-risk intersections where the view of the onboard sensors is obstructed.

4 General discussion

A general discussion of the work in this thesis and its scientific contributions starts here by addressing some key findings and continues with some methodological considerations and possible implications these findings could have on future active safety systems.

4.1 Discussion of results

4.1.1 Car drivers' behavior in car-to-VRU crashes

Paper I aggregated causation charts for 60 drivers involved in intersection crashes with VRUs, which enabled identification of the most common causation patterns. The results reveal that the most common events immediately prior to collisions were inadequate regulation of time for actions (about 68%) and inadequate distance between the car and VRU or objects in the traffic environment (about 25%). The most frequent contributing factor closest to these events was the failure to observe the VRUs. This was mostly due to reduced visibility, reduced awareness, and/or insufficient comprehension.

Although the methods for causation analysis differ, many of the contributing factors identified in Paper I are in line with previous studies. Räsänen and Summala (1998) have made an in-depth analysis of 97 car-to-bicycle intersection accidents, collected in four Finnish cities. Similar to the findings in Paper I, they showed that the drivers mainly failed to observe the bicyclist. They also found that the most common mechanism underlying these observation failures was the drivers' allocation of attention towards other road users and events instead of the bicyclists. This was in line with the results presented in Paper I.

Lenard and Hill (2004) made an analysis of 115 car-to-pedestrian accidents that occurred both in and away from intersections in England. Apart from the difference in inclusion of accident sites, their findings support those in Paper I; they found that factors related to observation failure ("failed to look", "looked but did not see"), inattention, failure to judge others' path or speed, and "obstruction by stationary/parked vehicle" were the most frequent.

Similarly, Molinero et al. (2008) did not distinguish intersection accidents from others. They have investigated mechanisms underlying 100 car-to-pedestrian accidents collected in Munich and Barcelona and several hundreds of car-to-bicyclist accidents collected in Nottinghamshire, Thames Valley, and Milan. In line with findings in Paper I, they found that the main human functional failures of the drivers were "non-detection in visibility constraint conditions", "expecting no perturbation ahead", and "expecting another user not to perform a maneuver". The "explanatory elements" comprise visibility constraints such as darkness, other vehicles, weather, and vehicle lighting. The data from bicyclist accidents was not sufficient to draw any conclusions about the causation mechanisms underlying these.

In conclusion, this comparison indicates that the findings in Paper I are limited neither to a specific region nor a road type. Moreover, it appears that the findings are not affected by the limited sample size. This comparison also shows that the findings from Paper I differ from the other studies. To be more specific, other studies did not show what brought about, for example, inattention. In other words, the other studies showed only the contributing factors and not causation patterns. Also, the other studies did not show whether multiple factors could have contributed to the accidents. By analyzing causation patterns by means of aggregated causation charts, it is possible to identify what causal relationship between the factors can be addressed.

4.1.2 Causation patterns for VRUs in car-to-VRU crashes

In Paper II causation charts for 57 VRUs involved in intersection crashes with cars were aggregated and the common causation patterns from the VRU perspective were identified. These VRUs were involved in the same crashes as the drivers in Paper I.

The analysis showed that 70% of the VRUs misjudged the reason for the low speed of the approaching car, expected that the driver would slow down, misjudged the gap in the traffic, suddenly changed their own behavior, overestimated their own conspicuity, or could not perceive a sudden action by the car driver. While about 80% of the drivers did not see the VRUs, only about 30% of the VRUs did not see the car. The VRUs did not see the car mainly due to temporary obstructions in the environment.

A literature review shows that there is a limited number of studies in which crash causation has been investigated from the perspective of VRUs. The study by Räsänen and Summala (1998) is one of those with findings similar to those in Paper II. These authors found that the most common mechanism underlying the accidents was the bicyclists' unjustified expectations about the behavior of drivers. This mechanism was found to be closely related to the road design and priority rule. Otte et al. (2012) shows that inadequate planning, interpretation, and observation issues are equally frequent for the bicyclists. Although these factors were identified in Paper II, inadequate planning and interpretation were more frequently attributed to the bicyclists in Paper II than observation. Otte et al. (2012) and Cuerden and Richards (2007) also found that pedestrians mainly did not see the conflict car. While observation issues were attributed to some pedestrians in Paper II, it was not the most frequent contributing factor. A possible explanation could be that these authors analyzed crashes that occurred in both intersections and non-intersections and involved various vehicle types, while Paper II focused on urban and suburban intersections and passenger cars. Another possible explanation could be that the proportion of accidents which occurred in darkness was larger in Otte et al. (2012) and Cuerden and Richards (2007) than in the data sample used in Paper II. However, this difference may also be explained by the differences in the methods used for causation analysis.

The similarities to the other studies reveal that the findings in Paper II could be generalized to some degree. However, the differences identified point out a need to further investigate the reason for them.

4.1.3 Car drivers behavior in car-to-pedestrian incidents

An objective of Paper III is to identify causation patterns in car-to-pedestrian incidents from the driver perspective. The incidents were video-recorded and showed the drivers and the traffic environment in a naturalistic driving study in Japan. Both intersections and non-intersection incidents were included in the study.

The results in Paper III show that the majority of the drivers in intersections misunderstood the situation due to visual obstructions and/or attention allocation towards something other than the conflict pedestrian. Half of the drivers in non-intersections were involved in incidents where the pedestrians behaved in an unexpected way.

A literature review showed that identifying causation patterns from video-recorded incidents seems to be a rather new approach. However, Dingus et al. (2006) have identified contributing factors for 108 car-to-pedestrian incidents collected in a naturalistic driving study. Similar to Paper III, they showed that visual obstructions were a common contributing factor and that drivers commonly focused on tasks not relevant for driving. Their findings differ from the findings in Paper III in the way that they show that many drivers were involved in the incidents due to inadequate skills, wilful behaviour, and impairment; these factors were not identified in Paper III. It is likely that these differences are due to the differences in the data collection procedures. More specifically, Dingus et al. (2006) used longer video sequences than in Paper III. Using longer sequences enables observation of driver behaviour and, consequently, factors such as impairment. The differences may also be due to the differences in the methods for causation analysis. A step in further research should therefore be to apply the modified DREAM to the sequences such as those by Dingus et al. (2006).

4.1.4 Comparison of causation patterns in Papers I, II and III

A comparison of the results in Papers I and II indicates that car drivers and VRUs are involved in accidents with each other for different reasons. As mentioned in Section 4.1.2, the majority of VRUs saw the car but they misinterpreted the upcoming situation and/or made an incorrect plan of action. On the other hand, the majority of the drivers did not notice the VRU.

A comparison of the causation patterns for drivers involved in accidents with VRUs (Paper I) and the causation patterns for drivers involved in incidents with pedestrians (Paper III) reveals both similarities and differences. Both studies show that visual obstructions in the traffic environment are common. However, such obstructions were even more frequently identified in the incidents. This may be related to the higher level of detail in the information available in the video-recordings or to differences in traffic environment between the countries in which the data were collected. To be more specific, in the video recordings it is easy to determine which objects are occluding the drivers' view. This is especially useful when it comes to vehicles and other road users that are moving. Such information is in general difficult to obtain from post-crash investigations of the traffic scene, or from interviews with the road users involved. Usually, the vehicles that temporarily obstructed the drivers' view have moved when the investigations teams arrive. In addition it may be difficult for the road users to recall whether there were objects that occluded their view immediately before the crash.

Furthermore, attention allocation towards something other than the upcoming conflict was a common factor in both crashes (Paper I) and incidents (Paper III). However, this was more frequently attributed to the drivers in the incidents. This difference can also be explained by the higher level of detail in the information available in the video-recordings. More specifically, the drivers' gaze direction was usually possible to observe in the video-recording of incidents. Based on the gaze direction the analyst could infer whether or not the driver was looking towards the conflict pedestrian. Again, obtaining this type of information in interviews with an investigation team or in a questionnaire may be difficult.

It should also be noted that contributing factors such as those related to driver's habits and experience were attributed to the drivers in crashes only (Paper I). This was not a coincidence. Identifying contributing factors from video-recordings alone limited the ability to identify these types of factors. This was especially valid if the video recording was trigger-based, Paper III, and driver behavior could not be observed for longer periods of time. Although mainly present in the incidents away from intersections, one should note that the unexpected behavior of pedestrians is more frequently attributed to the drivers in incidents than to the drivers in the crashes. This is also a type of information that is difficult to obtain from traditional investigation, i.e. it may be frequent in the intersection crashes as well but the drivers could not recall that the pedestrians' behavior deviated from their own expectations.

In summary, these differences and similarities between the results in Papers I–III show that data collected during traditional on-scene investigations and interviews with road users and the data obtained from video-recordings are more complementary than contradictory. In other words, to identify all contributing factors to an event, one should ideally analyze both video-recordings of the event and the information from interviews with the driver and VRU involved.

4.1.5 Pedestrian interactions with drivers in "normal passages"

In Paper IV, video recordings of the traffic environment and vehicle data from "normal" passages were analyzed. The analysis of these data showed that "normal" interactions between pedestrians and drivers could be used to further specify future active safety systems; hence, this type of traffic data is a complement to other data sources such as accidents (Papers I and II) and incidents (Paper III). By recognizing such interactions between these road users, risk assessment algorithms can more easily distinguish situations for which an action (e.g., warning) may be needed. The analysis showed that this assessment may be improved by exploring parameters related to pedestrian behavior, such as head orientation and distance to the edge of the road. None of these factors appear to be used in the current safety systems. Paper IV shows a way to incorporate calculations of the probability that a pedestrian will cross the road (or not) into the risk assessment algorithms; it also shows that this may improve the decision of the safety system should to undertake an action. Since the time scheduling of actions is usually included in the specification of functional requirements, these findings can also be viewed as a part of the specification process. Furthermore, the fact that head orientation is included in the risk assessment algorithms implies a need for image processing algorithms able to extract this information from video recordings. Given that current state-of-the art detection systems do not provide this type of information, this may be a major challenge for future active safety systems.

4.1.6 Implications for the development of active safety systems

The causation patterns identified in Papers I, II and III as well as the findings in Paper IV are a valuable basis for the development of active safety systems. The causation patterns reflect problems that the drivers and VRUs encounter in real world traffic, and can therefore support specification of the scenario type that an active safety system needs to address. This is later used to derive use cases, i.e. to specify what the system should do, and to define hypotheses for evaluation of the system.

The information contained in the causation patterns can also be used to derive requirements for the detection sub-system, such as sensor configuration, e.g. should the sensors be vehicle-based or infrastructure based, as well as communication needs and sensor operational conditions, e.g. should the sensors be able to detect the VRUs in adverse weather and light conditions. As explained in Section 4.1.5, the findings in Paper IV can also be used to derive the detection requirements in terms of the type of information that should be available from the detection sub-system.

For risk assessment algorithms, the causation patterns can provide some general information, such as that the VRUs are likely to misinterpret the traffic situation even when they clearly observe the vehicles (Paper II). Another example relates to the expectation of a warning; the driver may be surprised, since he is focusing on something other than the traffic situation (Papers I and III). This information can, along with the findings in Paper IV (see Section 4.1.5), be used as a basis for the time scheduling of actions. In Paper I, an attempt was made to determine the exact time when a warning should be issued to a car driver, based on the information in the causation charts. Given that the causation charts do not contain kinematic data (e.g. car speed and deceleration level), some key parameters were derived from a statistical database. While this estimation provides a useful overview of the time interval that should be “covered” by a warning system, a more accurate estimation based on a higher resolution of road user kinematics is needed. Here, a higher resolution refers to the data obtained from studies such as naturalistic driving during which signals such as speed and deceleration are sampled with a relatively high frequency.

Furthermore, the causation patterns identified in Papers I–III can also inform the design of the HMI in terms of its function and type of interaction and configuration. An example of the first could be if a warning should be issued to make the driver more attentive or to redirect the driver's attention. An example of the second, should a warning be auditory or tactical? An example of the configuration of the HMI could be if the HMI device is to be positioned in the vehicle or in the infrastructure.

To summarize, while causation charts give invaluable information in one sense, they cannot be used as the only information source in the development process of active safety systems. Real world data from other data sources are needed, including kinematics of the road users.

4.2 Methodological considerations

4.2.1 The role of accident data

The importance of multidisciplinary in-depth investigations of accidents has been highlighted by several researchers. In general, data from such investigations contain detailed information about the events leading to the accidents and the context in which they occur. The findings from Papers I and II show that not only factors related to the cognitive demand on the drivers and VRUs can be identified from in-depth data but also the factors related to drivers' and VRUs' expectations about each other's behavior, habits, and fatigue. These factors are difficult to obtain from other data sources that do not involve interviews with road users or some other types of self-report approaches. However, the quality of in-depth data may be affected by the ability of the road users to remember what they saw, how they felt, and how they usually behave in similar situations. Also, the willingness of road users to report some information may be crucial.

A way to address some of these shortcomings is to use well-formulated questions and to conduct well-structured interviews. The SNACS/DREAM provides tools that support the analysts in conducting interviews with road users. To "verify" the findings in Papers I and II, it would be useful to compare these findings with a naturalistic observation of similar situations where driver and VRU states are inferred by analysts (as it was done for the car-to-pedestrian incidents in Paper III).

Combining in-depth data and police-reported data is an approach that is often used to "make" the in-depth data representative. In Paper I, police reported data were used to select the accident scenario (passenger car-to-VRU accidents in urban X- and T shaped intersections) and to provide information on the context in which the accident type selected occurs. This was useful since, as explained in Section 4.2.4, an aggregation of all accidents involving VRUs would not be feasible. However, the issue related to the representativeness of the in-depth remains. It is still unknown if the in-depth cases analyzed are representative of a larger population. Ljung Aust (2010) suggested a method to over-bridge this issue by using mail survey data from road users involved in vehicle-to-vehicle accidents. Given that mail surveys are relatively inexpensive and can be sent to many people, a natural step in further research would be to apply the same method for car-to-VRU accidents. It is, however, important to note that the survey questions should be written in a way that is applicable for VRU accidents.

4.2.2 The role of naturalistic observation

The incident causation analysis in Paper III was inferred from video recordings of the drivers' upper body, feet and in some cases hands, adjacent parts of the vehicle interior, and the traffic environment. In that study the view of the surrounding traffic environment was limited to a forward sensing camera and two side view cameras, covering a total angle of approximately 180 degrees around the vehicle. The side view cameras were important to capture relevant information in intersections, especially when the driver was making a turn and the pedestrian entered from the direction of the turn.

The data recording was activated by an event-based trigger. The threshold was selected to capture as many safety-related incidents as possible. This is useful for automated data selection and is preferred when a large quantity of data is to be studied. However, selecting an appropriate threshold is challenging; although carefully selected, an event-based recording may result in the exclusion of some highly relevant safety-critical situations. This type of situation often occurs when the driver never realized the danger and never initiated braking. Another situation could be when the VRU took a preventive action, e.g., returned to the road edge. This can be solved partly by having continuous recordings such as those used in Paper IV. However, the problem of identifying safety critical situations would still remain. Although state-of-the art pedestrian detection systems (e.g. the one used in Paper IV) could address this issue to some extent, a complete recognition of all situations may require more advanced detection algorithms.

In conclusion, despite the risk that some cases were excluded (Paper III) due to selection of the threshold mentioned, the study did provide additional insights to the work in Papers I and II. This study using incident data enabled the recognition that for many of the incidents the driver failed to observe the VRU, due to a moving object that would not have been recognized in a study using accident data.

4.2.3 Analyzing causation by means of DREAM charts

Given that in-depth investigations provide detailed information about each accident, the methods used to analyze the information collected are still under discussions. Several approaches have been suggested, e.g., causation charts, and used mainly in other industrial domains.

Causation charts have been used for the investigation of occupational accidents since 1980s (Leplat and Rasmussen, 1987). As explained in Section 1.6, deriving charts that are truly useful for understanding accident causation requires well-defined methods for organizing contributing factors in a systematic way. More specifically, unique descriptions of accidents would not enable a comparison between them. It is, therefore, necessary to describe events leading to accidents, and the context in which they occur, in terms that are generally applicable to all of them.

In Papers I–III, the causation analyses were based on the DREAM. This method was chosen because it provides an accident model, a classification scheme, and classification method. The accident model is systemic, i.e. it views accidents as a mismatch between road users, vehicles, and the traffic environment, which makes it suitable for capturing the high complexity and dynamics of the road traffic today. Furthermore, the classification scheme and the classification method provide a set of contributing factors and analysis procedures. In addition, the DREAM classification scheme describes possible links between contributing factors based on the current knowledge about how various factors can interact. Together, the tools available in the DREAM ensure that the causation of every accident is treated in the same way, which limits the influence of analysts. In other words, DREAM enables the comparison of accidents, which is crucial for the development of active safety systems with recurrent effect.

The DREAM has previously been applied to the analysis of single and multiple vehicle accidents. It has not been used, however, for analysis of causation in car-to-VRU crashes or car-to-pedestrian incidents. Papers I and II show that the DREAM can be successfully used to analyze car-to-VRU crashes as well. More specifically, the information that was collected by investigations of the accident scene, interviews with the road users involved and eye witnesses could be categorized by the "classifiers" available in the classification scheme in DREAM. Except for some minor rephrasing in the analysis of VRU behavior (Paper II), e.g., "communication between drivers" has been changed to "communication between driver and VRU", the method could be applied in its existing form.

To enable the analysis of driver behavior in video-recorded incidents (Paper III), the DREAM was modified. The modifications were motivated mainly by the greater detail of information available in video-recordings than in the data from on-scene crash investigations. As already noted, in-depth accident investigations are typically based on retrospective analyses of the accident scene and interviews; recalling the entire sequence of events on a time basis from such a data source is nearly impossible. For instance, drivers may be able to remember that they did not see the conflict VRU at some moments before the crash, but recalling at which moments exactly they did not see the VRU may be difficult.

In the video recordings used in Paper III it was, on the other hand, possible to observe driver and pedestrian behavior for each time step. In particular, several variables related to drivers' behavior, including their gaze direction, facial expression, verbal expressions, feet interacting with gas and brake pedals, and steering wheel motion, could be observed in the videos. However, the DREAM did not contain rules on and examples of how to incorporate this type of information into the causation analysis. Therefore, the method modifications in Paper III mainly focused on formulating such rules and examples. A new “classifier” able to capture situations that occurred very suddenly and could not have been anticipated by the driver in advance was also defined, while some others were slightly rephrased to fit the information available in the videos.

After implementing the modifications, it was possible to classify all contributing factors and causal relationships between them that were inferred from the video recordings (Paper III). This indicates that the modified DREAM is a useful tool for the analysis of incident causation based on video-recordings. However, it should be noted that factors related to the cognitive demand on the drivers (e.g., effects of cell-phone use on the interpretation of the upcoming traffic situation) were not stated by the drivers as it is usually done in in-depth crash investigations; these were inferred by the analysts. Although this was done in a systematic way, there is a risk that the analysts’ impression of the cognitive demand does not correspond to the demand that the drivers really experienced in a given situation. In fact, obtaining such information solely from video recordings is difficult; it requires other sources of information. The idea that other data sources are needed to complement the data available in the video recordings is also supported by the fact that factors such as drivers’ habits, knowledge, and drowsiness could not be determined based on the video recordings. Accordingly, it is possible that some of these factors contributed to the incidents but were not captured by the analysis in Paper III. Some of the absent factors may be inferred from continuous video-recordings, but to ensure that these are correctly inferred, one would need to have statements from the drivers.

The DREAM was modified based on the analysis of incident causation from the perspective of drivers. It has not been used to explore the pedestrian behavior in the incidents. It is likely that some additional modification would be needed for such an analysis.

4.2.4 Aggregation of causation charts

Midtland et al. (1995) have concluded that formulating hypotheses on the basis of one accident is not useful because of possible differences between accidents. These authors have recognized that an aggregation of several accidents would yield the identification of common causes among these accidents and facilitate the formulation of hypotheses that reflect common problems. For this to be successfully done, causes and relationships between them have to be organized in the form of causation charts that can be aggregated.

The charts derived by means of DREAM (Papers I–III) can easily be aggregated in several ways. However, aggregating DREAM charts on a general level, e.g., all types of crashes regardless of type of road user involved and accident place, may be difficult to interpret and make use of, especially if the number of the accidents is low (which is usually true for in-depth data) and the variability among the accidents is high. It is, therefore, important to aggregate charts with a specific goal in mind.

The aggregation of DREAM charts from car-to-VRU crashes and car-to-VRU incidents in Papers I–III, was mainly driven by the applicability of the findings for the development of active safety systems. The charts were aggregated according to VRU type involved, road type, injury severity level, and trajectories of the cars and VRUs immediately prior to the accident. For each of these sub-categories, a set of common causation patterns could be identified, but many of them differed very little from the patterns made without any consideration to sub-categories. It should, however, be noted that Paper III showed some differences in the causation of incidents according to the car trajectories and their relation to the intersection. Given that the charts for car drivers in Paper I were not aggregated with respect to car trajectory, this should be further investigated in future studies.

4.2.5 Using incidents as crash surrogates

Incident causation viewed from the perspective of the car drivers involved in incidents with pedestrians was investigated by means of causation charts (Paper III). Using incidents as surrogates of crashes is not a new approach. For example, Hydén (1987) has shown that the behavior of road users in incidents is similar to their behavior in crashes. However, the use of causation charts for analysis of causation in incidents seems to be unexplored. This is not surprising since the availability of the data that could support derivation of such charts has been limited. It is only in recent years that great advances in technology development, such as smaller cameras that are relatively easy to fit into the vehicles in an unobtrusive manner and the ability to store large amounts of data, have enabled such an analysis.

The similarities between the findings in Papers I and III indicate that incidents may be used as surrogates of crashes when it comes to the analysis of causation mechanisms. However, clarifying this relationship should be a topic for further research.

4.2.6 From causation to requirements

Leplat and Rasmussen (1987) suggested two principles for identifying countermeasures by means of causation charts. The first is to eliminate a contributing factor. Although this principle is straightforward, it is not applicable in many situations, especially for complex traffic environments in urban areas where a great majority of the safety-critical situations involving VRUs occur. For example, a building that obscures car drivers' view of pedestrians coming from a given direction in an intersection cannot suddenly be removed. The other principle is to "break" causal relationships between factors (i.e. patterns) by introducing countermeasures that reduce the likelihood that given relationships will appear in the future. Applying this principle in the previous example would mean that car drivers are assisted by means of active safety systems when a pedestrian is approaching the road behind the building.

The causation analyses presented in Papers I–III were conducted to accommodate the second principle, i.e. to enable identification of countermeasures that could break causal relationships between contributing factors in car-to-VRU accidents. More specifically, following the Leplat and Rasmussen (1987) idea that causation charts need to be aggregated to facilitate the identification of recurrent factors and the relationships between them, the goal of these three papers was to suggest active safety systems that could break the causal relationship between the most common contributing factors. It was anticipated that this approach could inform the development of active safety systems that will have a recurrent effect, while the systems that are only relevant to few cases could be rejected.

The advantage of aggregated causation charts compared with approaches in which contributing factors are coded and aggregated individually by means of staple diagrams, for example, is evident. By coding and aggregating factors individually, it is only possible to eliminate a contributing factor. The result of such elimination is less evident, because causal relationships between the factors are consequently unknown. As shown in Papers I–III, safety-critical situations involving VRUs occur often as a result of the interaction of several factors. Analyzing these factors independently of each other may give an incorrect picture of how and why the critical situations occur. Statistical methods, such as correlation analyses between given contributing factors, can overcome this issue to some extent. However, the correlation analyses are applicable only to small numbers of factors at a time and require very large data sets.

Using the information contained in the aggregated charts for the purpose of development of safety countermeasures requires, on the other hand, a systematic approach. Based on the studies in Papers I–III, it can be concluded that a clear differentiation between common and uncommon contributing factors, or patterns is needed. To accommodate a consistent differentiation, a threshold value was defined in these papers based on the number of cases aggregated. Basically, if the frequency of a factor (or a link between two factors) did not reach this threshold value, the factor was regarded as uncommon. This seems to be a way forward, since a random determination of common factors may be affected by the analysts' opinions. It should, however, be noted that an identification of common factors is applicable only if the number of aggregated cases is large enough. From the aggregations conducted in Papers I–III it could be concluded that the number of cases aggregated should be about ten to reveal some common patterns; if the number of aggregated cases is low, it is difficult to know whether or not a common pattern is a coincidence.

Furthermore, the meaning of the causation patterns for development of active safety systems has been interpreted by means of "common logic" (Papers I–III). For example, given that the drivers often did not see the VRU prior to the crash due to physical obstructions in the traffic environment, it was suggested that an active safety system should help the drivers to "see" behind these obstructions. While "common logic" can be applied with satisfactory results, as it has been in this thesis, the thesis highlights the need for a systematic approach on how to interpret causation patterns to inform the development of safety systems. The work presented here could be seen as a start point for such a framework.

4.2.7 Applying a statistical approach to analyze data from normal interactions

An important role of the decision sub-system in an active safety system is to identify threats, i.e. to predict the risk of a collision. This includes prediction of the future states of the elements (road users, vehicles, road environment) in the traffic system. Given that behavior of VRUs is highly dynamic, predicting their future states accurately is a challenging task. A binary logit model was applied to assess what parameters affect the probability of crossing the road (Paper IV). This modeling approach was chosen for ease of interpretation. Other model forms were also explored, but they did not produce conclusive results.

The analysis in Paper IV showed that all parameters that were included in the logit model, except car-to-collision distance, were significant for the fitted value (probability). However, since the log likelihood ratio test showed that the *p*-value for the car-to-collision distance only slightly exceeded the significance level (0.05), it was not excluded from the model. This decision is also affected by the “practical” significance. As explained by Agresti (2007), it is important to consider the practical significance of a logit model in addition to statistical fit. More specifically, given that several other studies have shown that this parameter is crucial when pedestrians are making decisions to cross the road, it is likely that the low significance in our study was a “coincidence” originating from a limited data sample.

4.3 Directions for future active safety systems

4.3.1 Car driver support

The findings in Papers I–IV suggest some interesting directions for future active safety systems. One of these is that such systems should help drivers, even when their view is obstructed, to observe the VRUs in time. This implies that a cooperative system (i.e. based on wireless communication) is important for detection, since current onboard sensors often encounter line-of-sight problems in such situations.

Given that stationary objects, such as buildings and vegetation, are common obstructions in both crashes (Paper I) and incidents (Paper III), one could expect that a vehicle-to-infrastructure cooperative system should address some of the critical situations involving VRUs. An example of such a system is presented in the Section 3 of this thesis. In addition, the causation patterns show that temporary obstructions by non-conflict road users were common, especially in the incident data (Paper III). On the one hand, situations in which the VRU is first visible and then becomes occluded by other VRUs or vehicles may be possible to address by advanced tracking algorithms applied to detections obtained by onboard sensors. On the other hand, the analysis in Paper III shows that many pedestrians are not visible from the host vehicle prior to becoming occluded. While a vehicle-to-infrastructure system may be able to address these issues, it is, as discussed in Section 3, unlikely that such systems will be possible to install at all locations where temporary obstructions may be present. A possible solution involves a system based on vehicle-to-vehicle communication able to share information obtained by onboard sensors about VRUs in their vicinity. To be truly useful, the field-of-view of these sensors should be 360 degrees around the vehicle; as shown in Paper III, pedestrians are likely to cross both in front of and behind a slow moving vehicle. Another possible solution is to introduce a system based on communication between vehicles and some portable devices carried by VRUs. Given that cell-phones are widely used today, one could expect that vehicle-to-cell-phone communication may be a way to address safety critical situations involving temporary obstructions.

To help drivers to observe the VRUs, such a system should present information and warnings to the drivers. To gain acceptance, these will need to be issued only when the drivers would consider them relevant (needed and wanted). This is one of the key challenges with the interactive systems. In Paper IV, an approach to reduce the number of irrelevant warnings is introduced. It makes use of variables related to VRU behavior (e.g., head orientation) that are not usually obtained by state-of-the art detection systems. Consequently, more advanced detection algorithms would be required. It should also be noted that the cooperative solution involving portable devices would not be able to gather all these variables.

Another direction for the future active safety systems outlined, based on the findings in Papers I–III, is that such a system should help drivers to observe the VRUs under adverse weather and/or light conditions. This has implications mainly for the detection sub-system. Given that the vision-based sensors commonly used today for the detection of VRUs may encounter problems under such conditions, it is likely that future active safety systems would need to incorporate complementary types of sensors (e.g., IR-cameras) to address these problems.

The findings also indicate that active safety systems should make drivers more attentive and redirect the drivers' attention towards the most safety-critical event; drivers frequently did not see the VRUs because they focused on some other driving or non driving-related events or tasks. To avoid irrelevant warnings, risk assessment algorithms should take into consideration the state of drivers, i.e. determine whether a driver is focusing on the critical event. In Paper III, the analysis of video-recorded incidents showed that a combination of drivers' gaze direction and foot motion was an essential cue for determining whether the driver is aware of the conflict pedestrian. It is therefore likely that future active safety systems will need to incorporate similar data sources (e.g. eye-tracker and foot-view cameras) as well as risk assessment algorithms that can take these factors into account. The need for such sensors and algorithms is corroborated by the fact that several drivers could not interpret the upcoming situation correctly because they were stressed.

In addition, the findings in Papers I and III suggest that one direction for future active safety systems should be to help the drivers anticipate the upcoming situation. In particular, many drivers did not expect any VRUs to cross the road at the given location (due to priority rules or for some other reasons), or saw the conflict VRUs but did not expect them to enter the road. In many of these situations, the VRUs entered the road without showing their intent in any way, i.e. their behavior changed very suddenly; this is also supported by the findings in

Paper II. From this it follows that the information and warnings to the drivers will have to be designed in a way that will convince them that they should, in spite of their perceived priority, slow down or undertake some other preventive actions. Also, given that some sudden changes in VRU behavior may be difficult to predict within a time frame that allows drivers to react to warnings, it is likely that a combination with autonomous systems will be needed.

In summary, it can be concluded that future active safety systems should be able to help drivers to see VRUs in time: a) when their view is occluded, b) when they are focusing on other (non)driving related tasks, c) when they do not expect any VRUs to cross, and/or d) when VRUs actions are sudden. To provide this support, a combination of interactive and semi-autonomous functions will be needed. From this it follows that a variety of cooperative solutions should be combined with vehicle based sensors to facilitate the detection of as many safety critical situations as possible. Eye-tracking and foot-tracking features may be needed to allow accurate risk assessment and timely warnings. Cues from pedestrian behaviors can be used to reduce the number of irrelevant warnings. The HMI presenting warnings to drivers should be designed in a way that will not only capture but also redirect drivers' attention towards the most critical event.

4.3.2 VRU support

The findings in Paper II suggest that an active safety system able to increase the predictability of oncoming car drivers' behavior would be beneficial for many VRUs. More precisely, such a system should help the VRUs to correctly interpret the intentions of a car driver who has slowed down; many VRUs thought that car drivers had slowed down to let them cross while the driver had, in fact, slowed down for other vehicle(s). It should also help the VRUs to decide whether a car driver intends to slow down to let them cross; the VRUs commonly thought that the car driver was going to slow down and let them cross.

One way to achieve this goal, i.e. to predict drivers' intent and inform VRUs about it, would be to make use of information obtained via infrastructure based sensors. However, in order to keep the number of irrelevant warnings low, it is likely that such a prediction will require information from onboard sensors, e.g., drivers' gaze direction and foot motion. This, in turn, requires: advanced risk assessment algorithms; sensors that are currently not a part of state-of-the-art detection sub-systems in vehicles; a cooperative solution able to transmit information from vehicles to infrastructure; and/or some portable devices carried by the VRUs. In addition, it is likely that the VRUs will need more information than, for instance, a simple sound warning to understand the upcoming situation properly. It is also important that the information and warnings should convince them to wait in spite of their perceived priority. This is especially valid when taking into account that many VRUs may have expected the drivers to let them cross due to priority rules (Paper II). Accordingly, the HMI positioning and design will be crucial. When it comes to the HMI positioning, there are two options: in the infrastructure or as a part of portable devices. Given that each of these approaches has its own advantages and disadvantages, it is likely that a combination of these will be required.

4.4 Suggestions for future work

To explore causation in car-to-pedestrian incidents, DREAM charts were used. After modifications, the method could be successfully applied to classify contributing factors, and causal relationships between them, inferred from the video-recordings (Paper III). However, the method was only used to explore the car driver behavior in incidents with pedestrians. As shown in Papers I and II, analyzing the causation from the perspective of each road user involved in a safety critical situation is useful and provides more information than an analysis from the perspective of one road user only. Given that the method modifications (Paper III) were based on the causation analysis from the perspective of car drivers, it is likely that further modifications may be needed to capture the causation mechanisms from the perspective of pedestrians, i.e. explaining how and why the pedestrians got involved in a critical situation. A logical step in further research would be to explore whether such modifications are needed. It should, however, be noted that an increased image resolution may be required to make such an analysis, e.g., to see from a certain distance whether a pedestrian is observing the approaching traffic. Also, the usability of the DREAM method for video-recorded car-to-bicyclists incidents should be explored.

Another topic for future work should be to combine the causation analyses by using the DREAM charts and the time-history analysis of road user behaviors. For example, in conjunction to Paper III study, an annotation of the drivers' actions (e.g. their gaze directions) was carried out for each frame in the video recordings. This type of information can be useful for the development of active safety systems, e.g., defining algorithms to automatically determine the attention allocation of a driver, to see if this may lead to a safety critical situation. A combination of time-history data and causation mechanisms would be of major importance in the development of evaluation tests for active safety systems that reflect the real-world behavior of road users and their interactions.

An interesting topic for future research is related to the benefit for active safety systems of including models that take into account cues in VRU behavior such as head orientation. In the present thesis, a very limited data sample was used to predict intent of pedestrians to cross the road. Including a larger data sample from a variety of traffic situations is recommended. In particular, it would be useful to investigate differences and similarities between safety-critical situations and situations involving normal interactions between drivers and VRUs. This, in turn, implies a need for naturalistic driving studies where systems able to detect and track VRUs are used. It may also be worth combining such studies with on-site observations.

The thesis work makes it clear that each real-world data source analyzed here has its own limitations when it comes to the development of active safety systems. Police reported data are representative in general for a given geographical area, but these usually lack information on causation mechanisms. Data from in-depth accident investigations provide detailed information on what the road users involved were thinking and expecting, but this largely relies on interviews with these road users. Data from video-recordings and other sensors, collected in naturalistic settings, on the other hand, provide detailed information about the observable behaviors of road users; what they are really thinking, expecting, and intending to do is unobtainable. The thesis shows that a combination of these different sources is necessary to inform design of active safety systems. An avenue for future research should be to define a framework to show how various real-world data sources should be combined in a systematic way to address as many limitations of the individual sources as possible.

5 Conclusions

Four real-world data sources were explored in order to assess whether they reveal information useful for the development of active safety systems. The following conclusions can be drawn.

- The analysis of data from in-depth investigations of car-to-VRU accidents, by means of the DREAM causation charts, reveals that common causation patterns can be identified when these charts are aggregated. This was the case when both driver behavior and VRU behavior were explored.
- Similarly, a meaningful analysis of incident data, which consisted of video-recordings of driver, vehicle, and traffic environment, could be made by means of aggregation of DREAM causation charts. However, some method modifications were needed to accommodate more detailed information in video compared with the data from in-depth crash investigations.
- Causation patterns for drivers in car-to-VRU accidents differ from those for the VRUs. Causation patterns for drivers differ slightly between crashes and incidents, most probably due to differences in the information sources.
- The information from causation charts, in combination with police reported data, can be used to define overall requirements for detection, decision, and action layers in active safety systems. Example of this could be: to determine what type of support is needed to avoid accidents, to find out if detection of VRUs would require sensor systems to be installed in the infrastructure and if such installations require wireless communication, to identify the conditions under which sensors should operate, and to specify the type of warnings needed.
- To support the development of active safety systems addressing car-to-VRU crashes, information should preferably be derived from data collected in traditional crash investigations and from data collected in naturalistic observation of normal and safety-critical interactions between the car and the VRUs.
- Exploiting cues in pedestrian behavior, such as head orientation and distance from the road edge, which are observable in vehicle-based videos, is a promising way to improve the prediction of pedestrian intent to cross the road. This finding imposes additional requirements on video quality and real time analysis of this video.
- Future active safety systems should help drivers to notice the VRUs even when their view is obstructed by something in the traffic environment, as well as when drivers are focusing on something other than the conflict VRU. This implies a need for cooperative systems, advanced driver and VRU detection, and sophisticated HMI design. The VRUs would benefit from active safety systems that increase the predictability of car driver behavior.

6 References

Agresti, A. (2007). *An Introduction to Categorical Data Analysis.* John Wiley and Sons, Inc.

Akazawa, Y. (1999). Driving Safety Support System (DSSS) in the Aging Society. *Intelligent Transportation Systems.* Tokyo.

Almqvist, S., & Hydén, C. (1994). *Methods for Assessing Traffic Safety in Developing Countries.* Report Vol. 6, Issue 1, Building Issues Programme, Lund University, Lund, Sweden.

Andreone, L., Bekiaris, E., Guarise, A., & Mousadakou, A. (2006). *D2.1 – Requirements and use cases. Project report, Vehicle-to-Vulnerable roAd user cooperaTive communication and sensing teCHnologies to imprOVE transpoRt safety (WATCH-OVER).* Retrieved May 6, 2012, from http://www.watchover-eu.org/.

Antin, J., Lee, S., Hankey, J., & Dingus, T. (2011). *Design of the In-Vehicle Driving Behavior and Crash Risk Study; In Support of the SHRP 2 Naturalistic Driving Study.* Report No.: S2-S05-RR-1, The Second Strategic Highway Research Program (SHRP 2), Washington, D.C. Retrieved May 13, 2012, from http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2_S2-S05-RR-1.pdf

Anund, A., Dukic, T., Börsbo, B., & Falkmer, T. (2010). Piloting smart safe school bus: exploration of security gains from implementation of a driver support system, additional technical equipment and intelligent bus stops. *European Transport Research Review, 2*(3), 157-163.

Archer, J., & Vogel, K. (2000). *The Traffic Safety Problem in Urban Areas.* Research report no.: CTR2000-04, Royal Institute of Technology, Stockholm, Sweden.

Aycard, O., Spalanzani, A., Yguel, M., Burlet, J., Du Lac, N., De La Fortelle, A., . . . Steux, B. (2006). Puvame - New French Approach for Vulnerable Road Users Safety. *IEEE Intelligent Vehicle Symposium*, (pp. 2-7). Tokyo.

Baker, J. S. (1960). *Experimental Case Studies of Traffic Accidents: A General Discussion of Procedures and Conclusions.* Northwestern University, Traffic Institute, Evanston, Illinois, USA.

Benmimoun, M., Ljung Aust, M., Faber, F., Saint Pierre, G., & Zlocki, A. (2011). Safety analysis method for assessing the impacts of advanced driver assistance systems within the European large scale field test "euroFOT". *ITS European Congress.* Lyon, France. Retrieved May 13, 2012, from http://www.eurofot-ip.eu/en/library/presentations/

Björkman, K., Fagerlind, H., Ljung Aust, M., Liljegren, E., Morris, A., Talbot, R., . . . Verschragen, E. (2008). *In-depth accident causation database and analysis report.* Report no.: D5.8, SafetyNet project. Retrieved May 6, 2012, from http://ec.europa.eu/transport/wcm/road_safety/erso/safetynet/content/safetynet.htm

Brookhuis, K. A., de Waard, D., & Janssen, W. H. (2001). Behavioural Impacts of Advanced Driver Assistance Systems – An Overview. *European Journal of Transport and Infrastructure Research (EJTIR), 1*(3), 245-253.

Campbell, J. L., Richard, C. M., Brown, J. L., & McCallum, M. (2007). *Crash Warning System Interfaces: Human Factors Insights and Lessons Learned.* Report no.: DOT HS 810 697, National Highway Traffic Safety Administration (NHTSA), Washington, D.C.

Carsten, O. M., & Nilsson, L. (2001). Safety Assessment of Driver Assistance Systems. *European Journal of Transport and Infrastructure Research (EJTIR), 1*(3), 225-243.

Chan, C.-Y., & Bu, F. (2006). Vehicle-infrastructure integrated approach for pedestrian detection: feasibility study based on experimental transit vehicle platforms. *Transportation Research Board 85th Annual Meeting,* (pp. Paper nr. 06-0118). Washington, D.C.

Christoph, M., van Nes, N., Pauwelussen, J., Mansvelders, R., van der Horst, R., & Hoedemaeker, M. (2010). *In-vehicle and site-based observations of vehicles and cyclists; a small-scale ND field trial in the Netherlands.* PROLOGUE Deliverable D 3.4, TNO, Soesterberg, The Netherlands. Retrieved May 13, 2012, from http://www.prologue-eu.eu/fileadmin/content/Dokumente/PROLOGUE_D3.4.pdf

Coelingh, E., Eidehall, A., & Bengtsson, M. (2010). Collision Warning with Full Auto Brake and Pedestrian Detection - A practical Example of Automatic Emergency Braking. *13th International IEEE Annual Conference on Intelligent Transportation Systems,* (pp. 155-160). Madeira Island, Portugal.

Crandall, J. R., Bhalla, K. S., & Madeley, N. J. (2002). Designing road vehicles for pedestrian protection. *British Medical Journal (BMJ), 324*(7346), 1145-1148.

Cuerden, R., & Richards, D. (2007). On the Spot accident study – the characteristics of pedestrian accidents. *Behavioural research in road safety: Seventeenth seminar* (pp. 24-47). Department for Transport, England.

DeNicolao, G., Ferrara, A., & Giacomini, L. (2007). Onboard Sensor-Based Collision Risk Assessment to Improve Pedestrians' Safety. *IEEE Transactions on Vehicular Technology, 56*(5), 2405-2413.

Dingus, T. A., Klauer, S. G., Neale, V. L., Petersen, A., Lee, S. E., Sudweeks, J., . . . Knipling, R. R. (2006). *The 100-car naturalistic driving study, Phase II – Results of the 100-car field experiment.* Report no.: HS 810 593, National Highway Traffic Safety Administration (NHTSA).

Euro NCAP, .. (2009). *European New Car Assessment Programme (Euro NCAP)*. Retrieved May 10, 2012, from http://www.euroncap.com/testprocedures.aspx

Evans, L. (1990). An attempt to categorize the main determinants of traffic safety. *Health Education Research, 5*(2), 111-124.

Fleury, D., & Brenac, T. (2001). Accident prototypical scenarios, a tool for road safety research and diagnostic studies. *Accident Analysis and Prevention, 33*(2), 267-276.

Fleury, D., Girard, Y., Otte, D., Englund, A., & Pettersson, H. E. (1994). *In-depth investigation.* Forum of European Road Safety Research Institutes (FERSI) Group Report, Lyon, France.

Fröming, L., Schindler, V., & Kühn, M. (2006). Requirement Engineering for Active Safety Pedestrian Protection Systems based on Accident Research. In J. Valldorf, & W. Gessner (Eds.), *Advanced Microsystems for Automotive Applications 2006* (pp. 79-106). Springer Berlin Heidelberg.

Gandhi, T., & Trivedi, M. M. (2007). Pedestrian Protection Systems: Issues, Survey, and Challenges. *IEEE Transactions on Intelligent Transportation Systems, 8*(3), 413-430.

Gavrila, D. M., Kunert, M., & Lages, U. (2001). A multi-sensor approach for the protection of vulnerable traffic participants – the PROTECTOR project. *IEEE Instrumentation and Measurement Technology Conference*, (pp. 2044-2048). Budapest, Hungary.

Geruschat, D. R., Hassan, S. E., & Turano, K. A. (2003). Gaze Behavior while Crossing Complex Intersections. *Optometry and Vision Science, 80*(7), 515-528.

Grayson, G. B., & Hakkert, A. S. (1987). Accident analysis and conflict behaviour. In J. Rothengatter, & R. de Bruin, *Road Users and Traffic Safety* (pp. 27-59). Van Gorcum, Assen, The Netherlands.

Gregersen, N. P., & Nolen, S. (1994). Children's Road Safety and the Strategy of Voluntary Traffic Safety Clubs. *Accident Analysis and Prevention, 26*(4), 463-70.

Habibovic, A. (2008). *A review of accidents involving vulnerable road users.* Project report, Chalmers University of Technology, Gothenburg, Sweden.

Hakkert, A. S., Gitelman, V., & Ben-Shabat, E. (2002). An evaluation of crosswalk warning systems: effects on pedestrian and vehicle behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour, 5*(4), 275-292.

Hickman, J. S., Hanowski, R. J., & Bocanegra, J. (2010). *Distraction in Commercial Trucks and Buses: Assessing Prevalence and Risk in Conjunction with Crashes and Near-Crashes.* Report No.: FMCSA-RRR-10-049, Federal Motor Carrier Safety Administration, U.S. Department of Transportation, Washington, D.C.

Himanen, V., & Kulmala, R. (1988). An application of logit models in analysing the behaviour of pedestrians and car drivers on pedestrian crossings. *Accident Analysis and Prevention, 20*(3), 187-197.

Hollnagel, E., & Woods, D. D. (2005). *Joint Cognitive Systems: Foundations of Cognitive Systems Engineering.* Boca Raton, FL, USA: CRC Press / Taylor & Francis.

Huang, Q., & Miller, R. (2004). Reliable wireless traffic signal protocols for smart intersections. *Intelligent Transportation Society (ITS) of America 14th Annual Meeting.* San Antonio, Texas.

Huang, Y.-H. (2005). *A systemic traffic accident model.* Department of Computer and Information Science, Linköpings universitet, Linköping, Sweden.

Hydén, C. (1987). *The Development of a Method for Traffic Safety Evaluation: The Swedish Traffic Conflicts Technique.* Ph.D. Thesis, Lund University, Lund, Sweden.

Johansson, R. (2009). Vision Zero – Implementing a policy for traffic safety. *Safety Science, 47*(6), 826-831.

Kjemtrup, K., & Herrstedt, L. (1992). Speed Management and Traffic Calming in Urban Areas in Europe: A Historical View. *Accident Analysis and Prevention, 24*(1), 57-65.

Koenig, D. J., & Wu, Z. (1994). The Impact of a Media Campaign in the Reduction of Risk-taking Behaviour on the Part of Drivers. *Accident Analysis and Prevention, 26*(5), 625-633.

Kweon, Y.-J. (2011). Crash Data Sets and Analysis. In B. E. Porter, *Handbook of Traffic Psychology* (pp. 97-105). San Diego, CA, USA: Elsevier Inc.

Källhammer, J.-E., Pettersson, H., Eriksson, D., Junique, S., Savage, S., Vieider, C., . . . Stemme, G. (2006). Fulfilling the pedestrian protection directive using a long-wavelength infrared camera designed to meet both performance and cost targets. In P. P. Meyrueis (Ed.), *The International Society for Optical Engineering (SPIE), 6198,* pp. 619809.1-619809.11. Strasbourg, France.

Larsen, L. (2004). Methods of multidisciplinary in-depth analyses of road traffic accidents. *Journal of Hazardous Materials, 111*(1-3), 115-122.

Larsson, P., Dekker, S., & Tingvall, C. (2010). The need for a systems theory approach to road safety. *Traffic safety, 48*(9), 1167-1174.

Laureshyn, A., Ardö, H., Svensson, Å., & Jonsson, T. (2008). Application of automated video analysis for behavioural studies: concept and experience. *IET Intelligent Transport Systems, 3*(3), 345-357.

Lenard, J., & Hill, J. (2004). Interaction of road environment, vehicle and human factors in the causation of pedestrian accidents. *Proceedings of International Conference on Expert Symposium on Accident Research (ESAR).* Hannover, Germany.

Leplat, J., & Rasmussen, J. (1987). Analysis of human errors in industrial incidents and accidents for improvement of work safety. In J. Rasmussen, K. Duncan, & J. Leplat (Eds.), *New Technology and Human Error* (pp. 157-168). John Wiley and Sons Ltd.

Lindkvist, A., & Landerfors, L.-O. (2008). *Variabel hastighet – resultatrapport (Variable speed limits: a report on results).* Borlänge: Swedish Road Administration (SRA).

Ljung Aust, M. (2010). Generalization of case studies in road traffic when defining pre-crash scenarios for active safety function evaluation. *Accident Analysis and Prevention, 42*(4), 1172-1183.

Ljung Aust, M., & Engström, J. (2011). A conceptual framework for requirement specification and evaluation of active safety functions. *Theoretical Issues in Ergonomics Science , 12*(1), 44-65.

Ljung, M. (2002). *DREAM: Driving Reliability and Error Analysis Method.* Masters' Thesis, Linköping University, Linköping, Sweden.

Ljung, M., Fagerlind, H., Lövsund, P., & Sandin, J. (2007). Accident investigations for active safety at CHALMERS – new demands require new methodologies. *Vehicle System Dynamics, 45*(10), 881-894.

Lord, D. (1996). Analysis of Pedestrian Conflicts with Left-Turning Traffic. *Transportation Research Record 1538,* 61-67.

Manuszak, M. D., Manski, C., & Das, S. (2005). Walk or wait? An empirical analysis of street crossing decisions. *Journal of Applied Econometrics, 20*(4), 529-548.

McLaughlin, S., Hankey, J., & Dingus, T. (2009). Driver measurement: methods and applications. In D. Harris (Ed.), *The 8th International Conference on Engineering Psychology and Cognitive Ergonomics (EPCE); Held as Part of HCI International. LNAI 5639*, pp. 404-413. San Diego, California, USA: Springer-Verlag Berlin Heidelberg.

McLean, A. J. (2005). *Vehicle design for pedestrian protection.* CASR Report Series, Centre for Automotive Safety Research, The University of Adelaide, Adelaide, Australia.

Meinecke, M.-M., Obojski, M. A., Gavrila, D., Marc, E., Morris, R., Töns, M., & Letellier, L. (2003). *Deliverable D6: Strategies in Terms of Vulnerable Road User Protection.* Retrieved May 6, 2012, from Sensors and System Architecture for Vulnerable Road Users Protection (SAVE-U): http://www.save-u.org/

Meinken, K., Andreone, L., Guarise, A., & Sikora, A. (2007). WATCH-OVER – The concept of a cooperative system for vehicle to vulnerable road user communication. *20th International Technical Conference on the Enhanced Safety of Vehicles (ESV),* (pp. 07-0126). Lyon, France.

Midtland, K., Muskaug, R., Sagberg, F., & Jørgensen, N. O. (1995). *Evaluation of the in-depth accident investigations of the Swedish National Road Administration.* TOI Report: 296, Norwegian Institute of Transport Economics.

Miller, R., & Huang, Q. (2002). An Adaptive Peer-to-Peer Collision Warning System. *Vehicular Technology Conference (VTC),* (pp. 317-321). Birmingham, Alabama.

Mizuno, Y. (2005). Summary of IHRA Pedestrian Safety WG activities (2005) – Proposed Test Methods to Evaluate Pedestrian Protection Afforded by Passenger Cars. *19th International Technical Conference on the Enhanced Safety of Vehicles (ESV).* Washington, D.C.

Mohan, D. (2008). Road Traffic Injuries: A Stocktaking. *Best Practice & Research Clinical Rheumatology, 22*(4), 725-739.

Molinero, A., Perandones, J. M., Hermitte, T., Grimaldi, A., Gwehengerber, J., Daschner, D., . . . Fouquet, K. (2008). *Road users and accident causation. Part 2: In-depth accident causation analysis.* Retrieved May 6, 2012, from TRaffic Accident Causation in Europe (TRACE): http://www.trace-project.org

NHTSA. (2011). *Traffic Safety Facts 2009.* Report no.: DOT HS 811 402, National Highway Traffic Safety Administration (NHTSA). Retrieved May 9, 2012, from http://www-nrd.nhtsa.dot.gov/CATS/index.aspx

OECD. (1988). *Road Accidents: On-site Investigations.* Report prepared by the Organisation for Economic Co-operation and Development (OECD) Expert Group, Road Transport Research Programme, Paris, France.

OECD. (1998). *Safety of Vulnerable Road Users.* DSTI/DOT/RTR/RS7(98)1/FINAL, Report prepared by Scientific Expert Group on the Safety of Vulnerable Road Users (RS7), Organisation for Economic Co-operation and Development (OECD).

Otte, D., Jänsch, M., & Haasper, C. (2012). Injury protection and accident causation parameters for vulnerable road users based on German In-Depth Accident Study GIDAS. *Accident Analysis and Prevention, 44*(1), 149-153.

Otte, D., Pund, B., & Jänsch, M. (2009). A New Approach of Accident Causation Analysis by Seven Steps ACASS. *21st International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper no.: 09-0245.* Stuttgart, Germany.

Peden, M., Scurfield, R., Sleet, D., Mohan, D., Hyder, A. A., Jarawan, E., & Mathers, C. (2004). *World report on road traffic injury prevention.* Geneva, Switzerland: World Health Organization (WHO).

Qureshi, Z. H. (2007). Review of Accident Modelling Approaches for Complex Critical Sociotechnical Systems. In T. Cant (Ed.), *The 12th Australian Workshop on Safety Related Programmable Systems (SCS'07). Conferences in Research and Practice in Information. 86.* Adelaide, Australia: Australian Computer Society, Inc.

Rendon-Velez, E., Horváth, I., & Opiyo, E. (2009). Progress with situation assessment and risk prediction in advanced driver assistance systems: a survey. *The 16th World Congress for ITS Systems.* Stockholm, Sweden.

Retting, R. A., Ferguson, S. A., & McCartt, A. T. (2003). A Review of Evidence-Based Traffic Engineering Measures Designed to Reduce Pedestrian–Motor Vehicle Crashes. *American Journal of Public Health (AJPH), 93*(9), 1456-1463.

Rezaei, S., & Sengupta, R. (2007). Kalman Filter-Based Integration of DGPS and Vehicle Sensors for Localization. *IEEE Transactions on Control Systems Technology, 15*(6), 1080-1088.

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.

Saad, F. (2004). Behavioural adaptations to new driver support systems – Some critical issues. *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics,* (pp. 288-293). Den Haag, The Netherlands.

SAFER. (2008). *Test Site Sweden Field Operational Test; Final Report.* Report No.: 2008:1, SAFER Vehicle and Traffic Safety Centre, Gothenburg, Sweden. Retrieved May 13, 2012, from http://www.chalmers.se/safer/EN/projects/traffic-safety-analysis/tss-naturalistic-field/

Sagberg, F., Eenink, R., Hoedemaeker, L., Lotan, T., van Nes, N., Smokers, R., . . . Winkelbauer, M. (2011). *Recommendations for a large-scale European naturalistic driving observation study.* PROLOGUE Deliverable D4.1, TØI Institute of Transport Economics, Oslo, Norway. Retrieved May 13, 2012, from http://www.prologue-eu.eu/fileadmin/content/Dokumente/PROLOGUE_D4.1_01.pdf

Sandels, S. (1975). *Children in Traffic.* (J. Hartley, Ed.) London: Elek.

Sandin, J. (2008). *Aggregating Case Studies of Vehicles Crashes by Means of Causation Charts: An Evaluation and Revision of the Driving Reliability and Error Analysis Method.* Ph.D. Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Schmidt, S., & Farber, B. (2009). Pedestrians at the kerb - Recognising the action intentions of humans. *Transportation Research Part F, 12*(4), 300-310.

Scholliers, J., Heinig, K., Blosseville, J.-M., Netto, M., Leanderson, S., Engström, J., . . . Chen, J. (2007). *D16.3 Proposal of procedures for assessment of preventive and active safety functions.* Deliverable of PReVAL, a subproject of the PReVENT. Retrieved May 10, 2012, from http://prevent.ertico.webhouse.net/

Schulze, M., Irion, J., Mäkinen, T., & Flament, M. (2006). Accidentology as a Basis for Requirements and System Architecture of Preventive Safety Applications. In J. Valldorf, & W. Gessner, *Advanced Microsystems for Automotive Applications 2006* (pp. 407-425). Springer Berlin Heidelberg.

Singh, S. K. (2005). Review of Urban Transportation in India. *Journal of Public Transportation, 8*(1), 79-97.

Sklet, S. (2002). *Methods for accident investigation.* Report no.: ROSS (NTNU) 200208, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Spyropoulou, I., Yannis, G., Golias, J., Basacik, D., Chattington, M., Weare, A., . . . Regan, M. (2010). *Design of a naturalistic riding study - Implementation Plan.* Report No.: D5, 2-Wheeler Behaviour and Safety (2BESAFE). Retrieved May 13, 2012, from www.2besafe.eu

Steffen, B., & Seyfried, A. (2010). Methods for measuring pedestrian density, flow, speed and direction with minimal scatter. *Physica A: Statistical Mechanics and its Applications, 389*(9), 1902-1910.

Stutts, J. C., Hunter, W. W., & Pein, W. E. (1996). Pedestrian Crash Types: 1990s Update. *Transportation Research Record, 1538*(1996), 68-74.

Stutts, J., Feaganes, J., Rodgman, E., Hamlett, C., Meadows, T., & Reinfurt, D. (2003). *Distractions in Everyday Driving.* AAA Foundation for Traffic Safety, Washington, DC. Retrieved May 13, 2012, from http://www.aaafoundation.org/pdf/DistractionsInEverydayDriving.pdf

Sugimoto, C., Nakamura, Y., & Hashimoto, T. (2008). Development of pedestrian-to-vehicle communication system prototype for pedestrian safety using both wide-area and direct communication. *22nd International Conference on Advanced Information Networking and Applications* (pp. 64-69). GinoWan, Japan: IEEE Computer Society .

Svensson, Å. (1998). *A method for analysing the traffic process in a safety perspective.* Ph.D. Thesis, Lund University, Lund, Sweden.

Tan, H. S., & Huang, J. (2006). DGPS-based vehicle-to-vehicle cooperative collision warning: Engineering feasibility viewpoints. *IEEE Transactions on Intelligent Transportation Systems, 7*(4), 415-428.

Toroyan, T., & Peden, M. (2007). *Youth and Road Safety.* World Health Organization (WHO), Geneva, Switzerland.

Trafikanalys. (2010). *Road traffic injuries 2009.* Report no.: 2010:17, Trafikanalys (Swedish official statistics). Retrieved May 8, 2012, from www.trafa.se/publikationer

UNECE. (2008). *United Nations Economic Commission for Europe (UNECE). Statistical Database*. Retrieved May 9, 2012, from http://w3.unece.org/pxweb/database/STAT/40-TRTRANS/01-TRACCIDENTS/?lang=1

Walker, I. (2007). Drivers overtaking bicyclists: Objective data on the effects of riding position, helmet use, vehicle type and apparent gender. *Accident Analysis & Prevention, 39*(2), 417-425.

van Elslande, P., & Fouquet, K. (2007). *Analyzing 'human functional failures' in road accidents.* Project report: D5.1, TRaffic Accident Causation in Europe (TRACE). Retrieved May 6, 2012, from www.trace-project.org

van Houten, R., & Malenfant, L. J. (2001). ITS animated LED signals alert drivers to pedestrian threats. *Institute of Transportation Engineers. ITE Journal, 71*(7), 42-47.

Van Houten, R., & Nau, P. A. (1983). Feedback Interventions and Driving Speed: A Parametric and Comparative Analysis. *Journal of Applied Behavior Analysis, 16*(3), 253-281.

WHO. (2009). *Global status report on road safety: time for action.* World Health Organization (WHO), Geneva, Switzerland. Retrieved May 10, 2012, from http://www.who.int/violence_injury_prevention/road_safety_status/2009/en/

Victor, T., Bärgman, J., Hjälmdahl, M., Kircher, K., Svanberg, E., Hurtig, S., . . . Moeschlin, F. (2010). *Sweden-Michigan Naturalistic Field Operational Test (SeMiFOT) Phase 1: Final report.* Report No.: 2010:02, Gothenburg, Sweden. Retrieved May 13, 2012, from https://document.chalmers.se/download?docid=1773834060

Williams, B. (2004). *The continuous communications for vehicles (CALM) handbook.* Retrieved May 6, 2012, from http://www.tih.org.uk/images/c/c7/The_CALM_Handbook.pdf

Yang, J., Deng, W., Wang, J., Li, Q., & Wang, Z. (2006). Modeling pedestrians' road crossing behavior in traffic system micro-simulation in China. *Transportation Research Part A: Policy and Practice, 40*(3), 280-290.