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INTEGRATION OF CAR AND ROAD INFRASTRUCTURE DESIGN

CRASH SEVERITY AND OCCUPANT INJURY RISK EVALUATIONS IN FRONTAL REAL-WORLD CRASHES

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Obstacles are those frightful things you see when you take your eyes off your goal.

Källa: Henry Ford

Till Min Familj

ABSTRACT

During the last decade, traffic safety has not only been a matter of vehicle crashworthiness but an increasing interest can also be observed in the integration between vehicle and road infrastructure design. Research projects with a focus on merging these areas are however in their infancy.

In 1997, a new safety concept was introduced in Sweden, “Vision Zero”, whose goal was, and still is, to reach zero fatalities and serious injuries in road traffic. This vision is not only a new road safety strategy amongst others, it also urges a new way of thinking about the vehicle, road and driver as a system. Since the basis of the vision is human tolerance to trauma, the analysis of injury risk is a fundamental step in understanding occupant injury tolerance in the road transport system.

To reduce occupant injury risk in the road transport system, the different components included in the system need to be compatible. Roads have to be designed to avoid crashes or to mitigate the severity of crashes with all kinds of vehicles or objects.

The general objective of this project was to investigate frontal crash severity for different types of road designs, road-related parameters and different collision partners in two-vehicle crashes and single-vehicle crashes. Furthermore, an objective was to study the influence of crash pulse characteristics on injury risk in frontal crashes. One common solution adopted by road constructors is to use guardrails to avoid hazard areas and to reduce crash severity by for example extending duration of the crash. Further objectives were to study the dynamic characteristics of different guardrails at various impact angles and find if there is any influence of crash pulse duration on injury risk.

Studies I –III are retrospective studies of car crashes investigated in-depth in Sweden. Study IV is based on crash test results. The materials used in studies I-III were data from vehicle crash recordings of real-world impacts and vehicle inspections and study III also includes data from insurance files including hospital records and police reports. Data extracted from the measured crash pulse were change of velocity, mean and peak acceleration and pulse duration. In the main, moderate and more severe injuries sustained in frontal crashes were analyzed.

There was a 45% higher mean acceleration in crashes into rigid objects compared to deformable objects. A long duration of crash pulse does not lead to a high injury risk as long as the mean acceleration is low. Deformable guardrails show a relatively long duration and a large potential for injury reduction.

It was found that the largest average crash severity was found on undivided roads with the most severe impact type, frontal collisions with oncoming vehicles. Intersections were shown to have the second largest crash severity with oncoming vehicles as the most severe impact type. The most hazardous collision partner was shown to be HGVs and rigid objects.

The results show increasing crash severity for increasing posted speed limit, except for roads with a posted speed limit of 110 km/h. Roads with a speed limit of 110 km/h most often have separated lanes, indicating that separating lanes is important in reducing crash severity. The results also showed a lower crash severity on roads with lower road surface friction.

Most often change of velocity is used in studies of injury risk in vehicle crashes. Change of velocity is often well correlated to mean acceleration. However, this thesis shows that mean acceleration should be the primary parameter to be used as design guideline in the design of a crashworthy road transport system. High change of velocity could be handled as long as the mean acceleration is kept low.

The knowledge of crash severity and injury risk from various real-world conditions presented in this thesis could be used in the development and safety effect prediction of new safety technologies.

LIST OF PUBLICATIONS

This thesis is based on the following papers, which will be referred to in the text by their roman numerals.

I. Ydenius, A., **Frontal crash severity in different road environments measured in real-world crashes**. International Journal of Crashworthiness, Vol. 14, No. 6, December 2009, 525–532

II. Stigson, H, Ydenius A, Kullgren A., **Variation of crash severity depending on collisions with different vehicle types and objects.** International Journal of Crashworthiness, Vol. 14, No. 6, December 2009, 613-622

III. Ydenius, A., **Influence of crash pulse characteristics on injury risk in frontal impacts based on real life crashes.** Traffic Injury Prevention, (submitted), 2009

IV. Ydenius, A., Kullgren, A., Tingvall, C., **Development of a crashworthy system: Interaction between occupant injury potential and guardrails.** Accident Analysis and Prevention, (submitted), 2009

Paper II was designed and planned by Stigson, Ydenius and Kullgren. Stigson analyzed and wrote the paper under the supervision of Kullgren and Ydenius. Ydenius and Stigson had correspondence with the journal editor. Statisticians at Karolinska Institutet did the regression analysis in papers II and III. In Paper IV, the crash test was planned by Ydenius, Kullgren and Tingvall and performed by Monash University. Ydenius, Tingvall and Kullgren analyzed the results. Ydenius mainly wrote paper IV.

CONTENTS

LIST OF ABBREVIATIONS

ABS	Antilock Braking System
AEB	Autonomous Emergency Braking
AIS	Abbreviated Injury Scale
ASI	Acceleration Severity Index
BAS	Brake Assist. Adds extra brake force when applying the brakes
CCIS	Co-operative Crash Injury Study, British injury causation studies from in-depth accident data managed by Transport Research Laboratory (TRL)
CG	Centre of Gravity
Change of velocity	The difference between impact velocity and separation velocity
Contact velocity	Velocity of an object just before surface contact
CPR	Crash Pulse Recorder, mechanical EDR
Duration	The duration of the main crash pulse
EDR	Event Data Recorder
EES	Energy Equivalent Speed
ESC	Electronic Stability Control
Euro NCAP	European New Car Assessment Programme
FARS	Fatality Analysis Reporting System, fatal crash data in U.S., contracted by NHTSA
FUP	Front Underrun Protection on HGVs
GIDAS	German In-Depth Accident Study, In-depth studies from vehicle accidents in Germany
HGV	Heavy Goods Vehicles
HIC	Head Injury Criteria
Hybrid III	A frontal impact crash test dummy
IR	Injury Risk
ISA	Intelligent Speed Adaptation
MAIS	Maximum AIS
Mean acceleration	The average acceleration in the impact phase
NASS	National Automotive Sampling System, operated by NHTSA, accident data from minor to fatal vehicle crashes in U.S.
NHTSA	National Highway Traffic Safety Administration, part of the U.S. Department of Transportation
OIV	Occupant Injury Velocity
Overlap (%)	The amount of vehicle front involved in a frontal crash
Peak acceleration	The highest acceleration value during the impact phase
RPS	Road Protection Score, EuroRAP
SRA	Swedish Road Administration
THIV	Theoretical Head Impact Velocity

DEFINITIONS

In this thesis **road infrastructure** is defined as variables connected to the road for example road type, type of junction, road condition, crash object, road alignment and speed limit.

1 INTRODUCTION

The World Health Organization states that 1.2 million people worldwide are fatally injured every year as a result of road traffic crashes, and that one of the six most important factors is poor road design and roadway environment (Peden et al., 2004). Statistics from IRTAD (International Road Traffic and Accident Database) show that 24 000 car occupants in 28 OECD member states were fatally injured in the EU in 1998 (OECD, 1998). To break the trend in unacceptable numbers of casualties in road traffic accidents, goals were set up by the European Commission. In 2001, the European Commission made a declaration: "European transport policy for 2010: time to decide" with a target of 50% reduction of fatalities in the European Union by the year 2010 (EC, 2001). In order to achieve this target, a "European road safety action program" was published. One of the aims was an improvement of the road infrastructure.

To prevent fatal and serious injuries in the road transport system, a more holistic approach has been suggested when analyzing how different components in the system interact (Peden et al., 2004; Stigson et al., 2008; Stigson and Hill, 2009). Rather than focusing on single risk variables, the focus should be set on the interaction between the components of the road transport system and how they can be controlled (Underwood et al., 1993; Rasmussen, 1997; Peden et al., 2004; Linnskog, 2007). The model for a safe road transport system established by the Swedish Road Administration (SRA) also points out the importance of improving the safety of the road transport system (Linnskog, 2007). The SRA model "Safe Road Traffic" includes basic criteria for a safe road transport system and the model is a tool to determine discrepancies between the model and the real world.

With the exception of guardrails and support structure for road equipment, the safety design of roads in terms of crash severity reduction has to date only a few standards to follow. Road safety has not been prioritized in comparison with accessibility and aesthetics. The road safety measures has much been chosen from best practice (EC, 2003; Thomson et al., 2006) and the car industry has so far adapted their passive safety design to existing roads. If vehicle and road designers should be able to obtain a common knowledge regarding crashworthiness, it is important to define the level of vehicle crash severity not to exceed to avoid injuries. The predominantly used crash severity parameter is change of velocity, which ability to predict injury compared to mean acceleration is discussed in this thesis. The occupant injury risk is an important tool to define occupant tolerance and to describe the injury risk in different accident scenarios.

A fundamental key action towards a safe road transport system is to make it adapted to human behaviour (ATC, 2008) and taking human errors as a starting point. However, some elementary safety restrictions for road users must be followed in order to be able to protect the majority of road users from fatal or serious injuries in the case of a crash. Basic restrictions are; not exceeding speed limits, wearing seat belts and no driving under the influence of alcohol or drugs. If these restrictions are obeyed, the basic conditions are fulfilled to develop a crashworthy road traffic system with a design adapted to occupant injury tolerance.

The overall aim of this thesis was to study the integration of vehicle and road infrastructure design and to evaluate suitable crash severity parameters to be used in the design of a safe road transport system.

2 BACKGROUND

2.1 SAFE ROAD TRANSPORT SYSTEMS APPROACH

In the 1960s, the focus on vehicle safety first began and has undergone a continuous development. During the same period and for several decades, the first priority of road transport systems has been accessibility adapted to a continuous and growing flow of vehicles. The traffic system was more or less built to accept a number of casualties to promote traffic flow. At the time when the number of fatalities became a more important issue, more cost-effective traffic solutions with increased safety and preserved flow capacity were needed. Some examples of traffic safety measures carried out were roundabouts, intersections on highways that did not interfere with opposing traffic and intersections with left- and right-turn lanes. Several studies have analyzed the safety effectiveness of various measures of geometric features such as changes to horizontal road geometry, large-scale shoulder sealing, separate turning lanes at intersections and changing speed limits (Garber and Graham, 1990; de Leur et al., 1994; Corben et al., 1997; Harwood et al., 2003). Lum and Reagan (1995) however see one limitation in many studies since they mainly focus on a specific issue and do not examine the roadway as a whole. The research behind these measures has mostly been focused on factors relating to driver error and crash causation (Bédard et al., 2002), rather than finding the reason for injury outcome. Human errors and failings by the road user are predominantly the cause of crashes (Treat et al., 1979; Sabey and Taylor, 1980; Stigson and Hill, 2009) but to avoid or minimize the consequences of human errors there is a need to establish a total systems approach (Rasmussen, 1997; Stigson, 2009b). Strategic direction of road safety work has for that reason changed from individuals to the system which means that road deaths and injuries should be understood as a product of accident types, injury risk and the road system's lack of prevention.

A safe "Road transport system" makes demands on safety properties on all the parts included, such as vehicles, surrounding road areas and roadside objects, to minimize the consequences of a vehicle crash (OECD, 2002; Linnskog, 2007). So as not to break the chain of safe measures in the road transport system, the road user needs to stay within given limits. Even if each particular object may offer best practice in crashworthiness as verified by crash test results, the outcome in real-world crashes is sometimes different from results in the laboratory or the output from a numerical model. Figure 1 shows an example of a safety mismatch between road and vehicle. In this particular crash, a safe (5-star EuroNCAP rated) vehicle crashed into and over an approved guardrail type, within the posted speed limit, on a road with the highest safety

Figure 1. 5 star vehicle override a W-beam guardrail.

level (Road Protection Score according to EuroRAP European Road Assessment Programme)(Lynam et al., 2003). Nevertheless this crash ended up in a rollover on the wrong side of the guardrail. Figures 2 and 3 (Study II) show an example of a fatal crash with a sleeping driver who was trapped between the guardrails and crashed into the bridge pier. These examples show that even if each individual component (road, vehicle and driver) in the system fulfils the requirements, there is still a need to merge these components and analyze their individual characteristics as parts of a system.

Figure 2. Bridge pier with W-beam guardrail and cable guardrail.

Figure 3. Bridge pier with W-beam guardrail and cable guardrail, vehcicle trapped between the guardrails.

In 1997, the Swedish government approved a new road transport safety strategy called *Vision Zero*, with the long-term vision of no fatal or serious injuries within the road transport system (Tingvall and Lie, 1996). The strategy means that the road transport system should be designed based on biomechanical limits that road users can tolerate without sustaining serious injuries. It also means that as long as the road user obeys traffic rules, the designers of the system must establish that the system is safe to use. In several countries, it is now more common to see the road transport system as a dynamic system consisting of humans, vehicles and the road (ETSC, 2001; OECD, 2002; Peden et al., 2004; Wegman and Aarts, 2006; ATC, 2008).

Vehicle crashworthiness research has not been integrated enough into road environment research. During the last decade, the research on vehicle safety has slowly changed focus to also include road infrastructure. The Swedish Road Administration (SRA) has introduced a model for a safe road transport system based on the Zero Vision philosophy, where safety criteria have been linked to road, human and vehicle (Linnskog, 2007). The SRA model describes from a systems perspective the interaction between human, vehicle and road components and the property of achieving safe road traffic. In addition, the model describes necessary conditions of law observance that have to be fulfilled, on speed, seat belt and sobriety. The model has been used to identify deviations from the fulfilment of these criteria in order to handle weaknesses in the system in a more systematic way. The model was evaluated in terms of applicability to fatal injuries (Stigson et al., 2008) and serious injuries (Stigson and Hill, 2009) and the model was found to be useful although there is a need to develop the model to better identify weaknesses in the road transport system. Focusing on the interaction between components in a safe road transport system and how they could be controlled will be more important than focusing on risk variables. Therefore, there is a need to better understand the crashworthiness in the interaction between components to more effectively reduce the injury outcome.

2.2 ROAD SAFETY AND INFRASTRUCTURE GUIDELINES

An important outcome from road infrastructure safety projects is guidelines that help vehicle designers and parties responsible for road safety design in their decisions of safety zones, use of guardrails, placing of road equipment and design of side slopes (RISER, 2003). These guidelines can serve as an interface between road and vehicle safety. Although the different measures within the guidelines are assumed to be effective the quality and current approach to guidelines differs from country to country (Sörensen, 2007). A comparison of best practice guidelines between Australia, U.S. and Sweden concludes that the use of guidelines to changes the road safety in Australia and U.S. tends to be incremental rather than more fundamental like in Sweden (Delaney et al., 2002).

Two European road infrastructure projects are RISER and RANKERS. RISER is an EU-funded project, which set up guidelines for roadside design based on a national accident database and on existing roadside safety guidelines used across Europe (Thomson et al., 2006). The guidelines mainly define under what circumstances (distance from carriageway edge line, impact speed, stiffness and diameter) specific roadside objects should be treated as hazardous. Ranking for European road safety, RANKERS expresses the road safety level with a Road Safety Index (RSI) (Ramos et al., 2008). RSI is a three level colour evaluation scale of six different road infrastructure topics, road alignment, junctions, overtaking, roadside, pavement and road layout consistency. RSI has similarities with EuroRAP (European Road Assessment Program). EuroRAP, which is a collaboration of European vehicle organizations, determines public road stars according to a Road Protection Score (RPS). The Road Protection Score (RPS) is a scale for Star Rating roads for how well they protect the user from death or disabling injury when a crash occurs Stigson et al. (2009a) found that the RPS correlates with exposed crash severity and injury risk. However, future studies to validate the RPS with real-world crashes will be necessary. Therefore further studies are needed to further improve EuroRAP and the knowledge of injury risk in various road types is important.

Few guidelines are however expressed in terms of maximum acceptable crash severity, which constitutes important knowledge in the development of an interface between vehicle safety and road infrastructure design.

2.3 THE CRASH SEQUENCE

When the injury risk is evaluated for a given severity parameter, the injury outcome can either be reduced by changing that injury risk or by reducing the impact severity. Reduction of impact severity can be done either by lowering the impact speed or by distributing the energy of motion over a longer time. To elucidate the potential effect of impact severity reduction, it is useful to divide the crash into a crash sequence consisting of a chain of events. The crash sequence is here described for frontal impacts in Figure 4. The described sequence is a simplification since it does not include side impacts, rollovers and rear-end crashes. A situation which leads to a vehicle crash can be divided into separate events with a probability 1-p_x to revert to an earlier event, or a probability p_x to go to the next event. In the case of a multiple impact, the crash event returns from event 6 to an earlier event 5. In the irreversible part of the pre-crash phase (event 5), the main goal must be to lower the crash severity or redirect the vehicle into a less severe crash type. The vehicle safety system can apart from pre-braking also prepare occupants with respect to positioning and preloading of restraint systems to lower the occupant loadings. For each event, the road transport system must contribute to minimizing the likelihood of reaching the next event in the crash sequence. This thesis is focused on events 5 and 6. In each event there are vehicle-related and road-related factors that reduce the probability p_x.

This thesis confines itself to the part of the road transport system that directly relates to passenger two-vehicle or single crashes and their collision partner but does include driver behaviour.

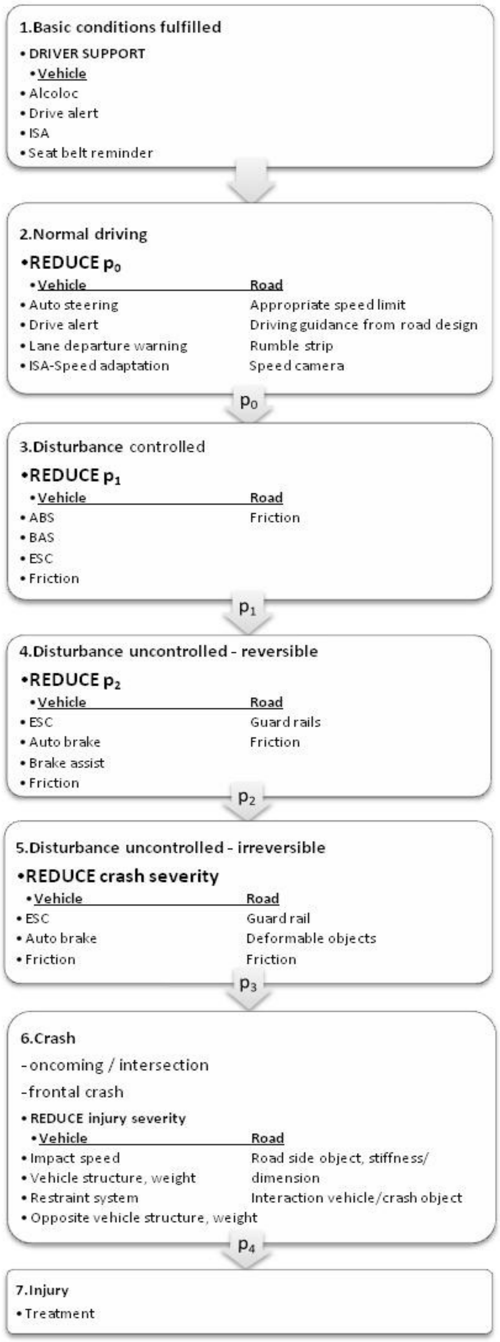

Figure 4. Modified crash sequence with a chain of events.
Source: (Tingvall and Lie, 2008; Rizzi et al., 2009)

A short description of the seven events in the crash sequence (Figure 4) is described below:

1. A safe road transport system requires some important basic conditions to be fulfilled. The driver has to have his seat belt buckled, follow the speed limit and be sober. The supporting system in the vehicle helps these conditions to be fulfilled.
2. In a normal driving situation, the driver will sooner or later make a mistake. With driver supporting systems and roads that support the driver to make the right decisions, p_0 the probability of passing into a controlled disturbance can be reduced.
3. Disturbance controlled – the driver is in a critical situation caused by for example an animal appearing on the road, drowsiness, an oncoming vehicle in the wrong driving lane, rule violation or speed violation. With driver supporting systems and speed adapted to friction, p_1 can be reduced.
4. Disturbance uncontrolled, reversible – the driver is in a critical situation and has partly lost control of the vehicle. Without driver supporting systems it is very difficult to reduce p_2 i.e. the situation turns probably into event 5.
5. Loss of control, irreversible – the driver cannot any longer avoid an impact. Posted speed limit/driving speed determines the kinetic energy of the vehicle prior to impact. Given a certain speed at impact, braking can reduce the impact speed, either by the driver or by supporting systems aimed at automatically braking or steering the vehicle. Road objects designed to absorb kinetic energy or redirect the vehicle from a more severe crash type, contribute to the reduction of crash severity.
6. For a given energy of motion, injury severity depends on how the energy of motion is distributed over time. Factors that affect the energy distribution are weight, stiffness and dimension of the collision partner in both single and two-vehicle collisions. With interior safety systems such as seat belt technology and airbags, the occupant ride down acceleration can be reduced.
7. Treatment, the last event, is not discussed in this thesis but is a factor for further studies on the influence of time to injury treatment and type of injury treatment on long-term consequences and fatality risk.

2.4 DOSE-RESPONSE MODEL

A theoretical tool to show the link between crash severity and occupant injury outcome is a dose-response model. The basic idea is to expose objects with a varying external dose of any kind and to study the response of the objects. The dose-response concept has also been applied in the road transport safety field (Evans, 1994a; Norin, 1995). One central component in the road transport system is the human being and the knowledge of his/her tolerance to injury. A theoretical approach to this problem is to understand and apply a Dose-Response Model to the "Road transport system". The **Dose-Response Model**, presented for example by Norin and Isaksson-Hellman (1995) and Kullgren (1998, 2008) describes the relationship between injury outcome and exposure (Figure 5). The dose is a quantity of crash severity i.e. a quantity reflecting the collision forces of the vehicle. The response is represented by the occupant injury outcome.

Figure 5 illustrates how injuries could be reduced, either by reduction of crash severity (1), reduction of the number of crashes (2) or by lowering the injury risk (3) (Kullgren, 1998). The application of the Dose-Response Model can be described as follows: Reduction of crash severity, (1) in Figure 5, is essential in situations where the passive safety of vehicles is insufficient to ensure occupant safety. With speed controlling systems, collision mitigation braking systems and flexible, forgiving roadside areas, the safety level of existing less safe cars could partly be compensated. In order to influence the total exposure (2), a range of countermeasures are possible both on road design and vehicle crashworthiness. Several studies have shown major reductions in vehicle crash involvements leading to occupant injuries, for cars fitted with ESC (Aga and Okada, 2003; Dang, 2004; Farmer, 2004; Lie et al., 2004; Bahouth, 2005; Ferguson, 2007) compared to the less effective antilock braking system (ABS) (Farmer, 2001). Countermeasures in road and roadside geometry can reduce casualty crash frequencies by more than 20% according to Corben (1997). Corben also suggests that changes to horizontal road alignments are an effective measure. In order to reduce the injury risk (3), increased passive safety of vehicles and roads are both contributing factors. Hägg et al. (2001) and Kullgren et al. (2002; 2008) have shown that there still is potential for decreasing injury risk by increasing vehicle passive safety. Increased road safety and vehicle safety both integrated and adapted to human tolerance give an opportunity for much injury risk reduction.

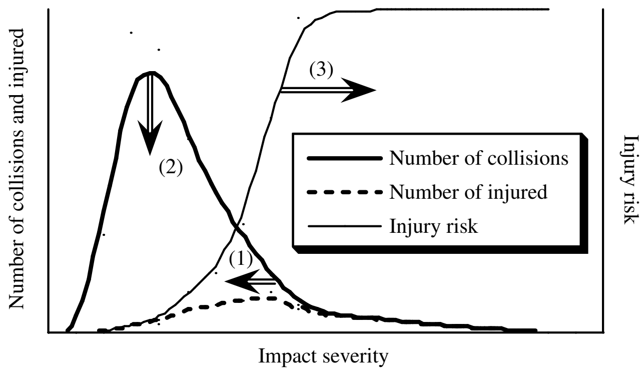

Figure 5. Dose-Response Model. (Kullgren, 1998).

2.5 CRASH SEVERITY

Crash severity is a primary factor in crashworthiness and occupant injury research. The predominantly used crash severity parameter in safety research is the change of velocity during the collision phase (Evans, 1994b). A choice of parameters to express crash severity exists as well as techniques for measuring or calculating the parameters.

2.5.1 Crash severity estimated from structural deformation

There are several methods to calculate crash severity from structural deformation. Commonly used methods are using computer aided reconstruction programs such as CRASH3 and Win Smash. The output from these methods is speed-related parameters such as change of velocity. One limitation of many studies, however, is the limited accuracy of crash severity estimations. In retrospective studies, CRASH3 is commonly used software. Studies of CRASH3 and WinSmash (derivate of CRASH3) by Lenard et al. (1998) and Niehoff and Gabler (2006) show large differences in the accuracy of estimates of the change of velocity for various vehicle types, stiffness and impact modes. The accuracy also depends on the crash type. In real-world crashes, variations in crash types and crash modes make it difficult to obtain reliable results from computer reconstruction software. One example such as small overlap head-on oblique crashes into vehicles or objects is proven not to be most suitable for crash reconstruction programs (Stucki and Fessahaie, 1998; Neptune, 1999; Niehoff and Gabler, 2006). Crash severity measurement with Event Data Recorders (EDRs) can be used to supplement the estimates of change of velocity from reconstruction programs (Gabler et al., 2004). According to Gabler et al. (2003) it is however not an obvious advantage of EDRs compared to computer reconstruction of crash severity estimations.

2.5.2 Crash severity from crash recorders (EDR)

Vehicle-installed EDRs also open up new possibilities for measuring crash severity parameters other than change of velocity. There is however a need for a better classification of crash severity because it was not identified during the period when on-board measuring accelerometers were expensive and complicated to adapt for large vehicle fleets. In contrast to acceleration, the commonly used change of velocity does not consider the duration of the crash pulse and vehicle acceleration has been shown to well explain the severity of crashes (Krafft et al., 2001; Ydenius and Kullgren, 2001; SIS, 2003; Gabauer and Gabler, 2008a; Kullgren, 2008). Vehicle acceleration is especially important for road designers and is well established in European test standard EN 1317 (European Committee for Standardization, 1998) for road restraint systems (CEN, 1998a; CEN, 1998b).

2.5.3 Impact speed

One dominating factor that affects crash severity is impact speed. One study has shown that effective driver protection is reachable at frontal impacts up to 80 km/h (Pipkorn et al., 2005). The EuroNCAP test speed of 64 km/h is chosen to represent a 5% risk of AIS3+ injury (EuroNCAP, 2009). The posted speed limit is an important means for controlling the impact speed. Reduced impact speed is shown to have broad effect on crash involvement, occupant injuries and fatalities (Finch et al., 1994; Kloeden et al., 1997; Buzeman et al., 1998). Several studies show the influence of speed limit on crash severity (Nilsson, 1982; Joksch, 1993; Renski et al., 1999; Nilsson, 2004). These studies do not measure crash severity inside the vehicle but use either posted speed limit or estimated impact speed. Measured crash severity with EDRs in the vehicle on various road types and environments could increase the quality of the evaluation of the correlation between speed limit, crash severity and injury outcome. Techniques to reduce impact speed automatically (AEB) prior to impact are a promising way (Krafft et al., 2009) to lower crash severity. Coelingh et.al. (2007) show considerable reduction in impact speed with AEB systems. AEB used in heavy goods vehicles (HGV) would be an effective way to reduce the injury outcome in crashes between cars and HGV (Strandroth, 2009).

2.5.4 Crash pulse duration

Crash pulse duration alone is not considered to be a crash severity parameter but has an important influence on mean acceleration in a crash. An example of crash type that shows large differences in crash severity and crash pulse duration is crashes into guardrails. Guardrails is expected to lower crash severity than without (Elvik, 1995) and keep rebounding speed low (Naing et al., 2008). Frontal crashes into flexible guardrails can lead to large changes of velocity but low acceleration levels because of the extended pulse duration (Mills and Harding, 1983; Huang, 2002). The reversed relationship is for rigid guardrails with low change of velocity and high mean and peak acceleration (Study IV). The results in study III show that duration does not have a negative influence on injury risk.

Depending on crash mode, the variation of crash pulse duration can be large (Huang, 2002). Geigl et al. (2003) have shown the influence of crash pulse duration on chest and head loads with PC-crash modelling. They showed that a shorter crash pulse (with constant change of velocity) leads to a higher mean acceleration and thus a higher relative velocity between occupant and vehicle early in the collision phase, resulting in an increase in chest peak acceleration and head acceleration. This clearly shows that keeping acceleration low with longer duration leads to lower loadings on the occupants.

Flexible objects (study II) and changes of vehicle structure (Giess and Tomas, 1998; Wågström et al., 2005; Park et al., 2009; Pipkorn, 2009) are shown to have a positive effect on crash severity and occupant loadings. Another possibility for reducing occupant loadings is vehicle interior safety systems such as smart airbags and seat belts which not only address severe injuries but also AIS1 neck injuries (Kullgren et al., 2000a). Smart safety systems are designed to prepare certain systems in the pre-crash phase and adapt the grade of deployment to crash severity.

2.5.5 Intrusion

Occupant compartment intrusion is not considered in the analysis of severity parameters in this thesis. In crashes with intrusion, often the case in low overlap crashes (Lindquist et al., 2004), the cause of injury is increasingly dependent on the intrusion (Thomas et al., 1995). Real-life data shows that for example lower limb injuries, injuries with high risk of impairment (Malm et al., 2008) and affected quality of life (Morris et al., 2006), occur even for moderate intrusion (Thomas et al., 1995). One study by Delannoy et al. (2005) shows from frontal offset crash tests examples with no intrusion at a mean acceleration of 13 g in offset frontal crashes. However, in small overlap crashes intrusion can appear for much lower mean acceleration (Kullgren et al., 1998). For these crashes with extensive intrusion, other parameters need to be considered to best correlate with injury.

2.5.6 Crash severity parameters

To be able to design the most effective interventions it is necessary to identify the crash severity parameters most relevant and correlated with injury outcome. Furthermore if the crash severity distribution were known for various road environments, it would be possible to define hazardous road areas and also to determine the actual occupant injury risk in these road environments.

Most of the current databases include crash severity estimations done by computer software for example NASS, FARS, CCIS and GIDAS. Projects with vehicle-installed EDRs with the capability to measure parameters other than those that can be obtained from reconstruction programs have appeared more frequently.

Extracts from the most commonly used crash severity parameters in crashworthiness research are briefly described below:

Delta v- Δv, "*Vector difference between impact velocity and separation velocity"* (SIS, 2002) is one of the most commonly used parameters to express crash severity in real-world crash data. Change of velocity is a vector and typically determined from deformation measurements on the vehicle that are fed into a software program, for example CRASH3. Since the last decade, change of velocity can also be calculated from the crash pulse measured from EDRs already installed in many brands of vehicle. The limitation with change of velocity appears for example in crashes when the vehicle is not stopped to zero such as in small overlap crashes. In these crash types, the output from reconstruction programs has relatively large errors (Lenard et al., 1998). Kullgren et al. (1998) suggest that reconstruction of small overlap crashes is preferably done with onboard measurement techniques and with acceleration-based severity parameters.

EES – Energy Equivalent Speed, "The equivalent speed at which a particular vehicle would need to contact any fixed rigid object in order to dissipate the deformation energy corresponding to the observed vehicle residual crush" (SIS, 2002) is described by Zeidler et al. (1985). EES, which is not a vector, can work with partial information from the crash (i.e. the damage profile from one vehicle only), as it is only a measure of the energy dissipated by that vehicle. The results of EES can be misleading if you consider that a small change of velocity at high impact speed can have the same kinetic energy dissipated as that of a large change of velocity at low impact speeds. Implications of EES and change of velocity for injury mechanisms is shown by Berg et al. (1998).

Mean acceleration – $\bar{a} = \Delta v / \Delta t$ Mean acceleration (SIS, 2002) considers, apart from Δv, the duration of the crash pulse. A given amount of energy, with the same change of velocity, can be distributed in a short or long crash event, with a large influence on acceleration forces. Mean acceleration is a candidate to use in a wider range of crash modes with various pulse shapes and durations. To determine the occupant injury risk in full-scale crash tests of roadside objects, Accident Severity Index (ASI) is used according to the procedure in EN1317-1 (CEN, 1998a). ASI has also been investigated as injury predictor in other crashes than single vehicle crashes (Schram et al., 2006). ASI is a dimensionless quantity and is a scalar function of time. ASI sets limits on longitudinal, lateral and vertical vehicle acceleration.

Peak acceleration – Peak acceleration (SIS, 2002) is the largest pulse value during the crash. The peak acceleration value depends on sample frequency. The peak value is at the 3 ms level.

OIV – Occupant Impact Velocity described in Ross et al. (1993) is equivalent to THIV (Theoretical Head Impact Velocity) in head-on impacts and is a metric of occupant contact velocity, according to a flail space model. The flail space model assumes the occupant to be an unrestrained point mass. Measured vehicle kinematics is used to compute the difference in velocity between occupant and occupant compartment at the instant the occupant has displaced either 0.3 m laterally or 0.6 m longitudinally.

The ability to predict injury varies with crash type, among the crash severity parameters mentioned above. More research is needed to refine the findings of appropriate parameters for various crash types. The different methods used to calculate or measure crash severity parameters have variable accuracy. Besides a truly predictive severity parameter, it is important to have an awareness of the influence that the accuracy of the calculated or measured parameter has on the calculation of injury risk.

2.6 EDR TECHNOLOGY

Event Data Recorder (EDR) is a generic term for a device mainly designed to measure acceleration in one or more directions. Although there are EDRs that additionally measure a lot of pre-crash information, the EDR results in this thesis only focus on crash severity. The first attempts to measure crash severity in real-world impacts were mainly started in the US, initiated or requested by the NHTSA (Hudson, 1972; Teel et al., 1974; Sherwin and Kerr, 1979). Other EDR projects have been described by Wilkie et al. (1989), Salomonsson et al.(1991), Fincham et al. (1995) and Kullgren et al. (1995). Cheaper and more reliable electronics have made the EDRs of today more advanced. The German company Mannesmann – Kienzle (presently called Siemens VDO) produces an EDR that is sold to car owners. The results from the recordings have also been used for occupant injury research, for example Krafft et al. (2001). Folksam, a Swedish insurance company, has installed EDRs in a limited number of car makes since 1992 with the aim of studying the correlation between crash severity, such as vehicle acceleration, and injury risk (Kullgren, 1998). Axa Winterthur in Switzerland started an insurance project in 2008 with EDRs mounted in vehicles owned by young drivers with one aim being to study driver behaviour prior to crash as well as the correlation between injury outcome and crash severity. A number of car manufacturers have sophisticated EDRs, such as Volvo, GM, Ford and Toyota, with the technical capacity to record crash severity data from airbag sensors.

Although EDRs open new possibilities for crash severity measurements, it is still an expensive component if no compromise regarding recording time (Niehoff et al., 2005), ability of multiple event recording or measurement direction is made.

2.7 INJURY RISK

Step 6 in the crash sequence (Figure 4) is the risk of sustaining an injury at a given level of crash severity. In the biomechanical field, injury risk is expressed as a function of loadings on the human body. In the area of vehicle crashworthiness, injury risk can be expressed as the ratio of the number of injured to the number exposed, as a function of crash severity level. An early attempt to express injury risk (IR) was made by Gadd

(1966) who found that injury risk is related to impact duration times mean body acceleration. Wood and Simms (2002) proposed on basis of Gadds result that, for a given vehicle population, the mean occupant acceleration in a collision is proportional to vehicle acceleration $\bar{a}$. As the impact durations between two colliding cars are identical, then the injury risk can be considered as being a function of mean acceleration of the occupant compartment as $IR \propto \bar{a}^{2.5}$. Several studies of injury risk functions have been presented, for example by Norin (1995) and Evans (1994b). In these studies, the crash severity, most often expressed as change of velocity, was estimated by using crash reconstruction techniques. More recent studies, where crash severity has been measured with EDRs, have been presented for example by Krafft et al. (2001), Kullgren et al. (2008) and Gabauer and Gabler (2008a, 2008b). EDRs have the possibility of increasing the quality of estimates of crash severity, which have been shown to have an important effect on estimates of risk functions (Kullgren, 1998).

Since injury risk is an important tool in assessing injury tolerance limits for the most vulnerable vehicle occupants, it is also important to incorporate present knowledge of the vehicle occupant factors that influence injury risk. Such factors could be age, gender and position in the vehicle (Bédard et al., 2002).

Errors in data input are important to consider since it affects the calculated injury risk (Kullgren, 1998). One dominating factor to errors in injury estimations are errors in impact severity calculations (Funk et al., 2008). Misclassification of injury level, which in many cases is done by the police, is also a source of error (Aptel et al., 1999; Alsop and Langley, 2001; Amoros et al., 2006; Tsui et al., 2009) together with misclassification of seat belt use (Schiff and Cummings, 2004; Guo et al., 2007). Qualitative impact severity estimations and injury classifications are therefore important in order to achieve reliable injury risk estimations.

The improved possibilities of using EDRs in larger vehicle fleets have instigated new research projects. The EDR makes it possible to validate present test methods. Gabauer and Gabler (2008b) have used EDR data to compare the ability of ASI, OIV and change of velocity to discriminate between maximum injury level (Figure 6,8 and 9). The results show a significant correlation between ASI and maximum injury, but neither ASI nor OIV were found to offer a significant predictive advantage over change of velocity. The results emphasize the need for improvements in ASI and OIV criteria to better correlate with injury in other than guardrail cases. Gabauer and Gabler (2008b) see improved injury criteria as a possibility for the roadside safety community to make better decisions in the implementation of roadside hardware.

Gabauer and Gabler (2008a) have presented one of a few studies of injury risk related to peak vehicle acceleration (Figure 7). In 145 frontal crashes with EDRs, the crash severity was expressed as the largest 50 ms and 10 ms average acceleration value from the peak acceleration pulse. The probability curve was calculated with binary logistic regression.

Norin and Isaksson-Hellman (1995) have suggested a method to predict the safety potential of design features in certain crash configurations before the system is exposed to real traffic conditions. The method uses a combination of simulation data and crash data. The method can describe the injury risk for different parameters, for example velocity change, mean acceleration, seating position and other relevant road-related parameters.

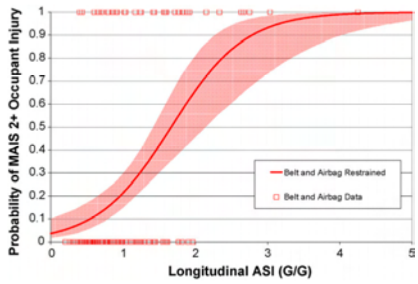

Figure 6. ASI – MAIS 2+ injury risk. (Gabauer & Gabler 2008b)

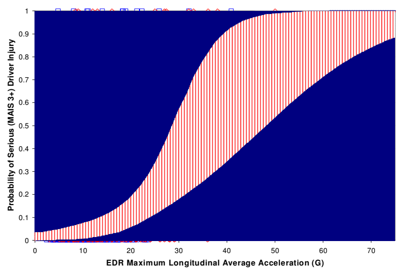

Figure 7. Mean acceleration – MAIS3+ injury risk, (Gabauer & Gabler 2008a)

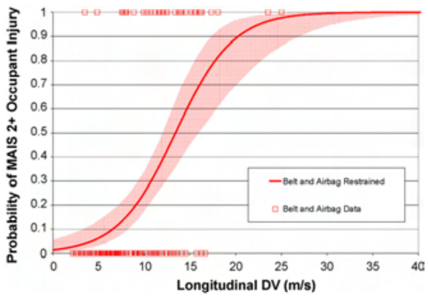

Figure 8. Change of velocity – MAIS 2+ injury risk. (Gabauer & Gabler 2008b)

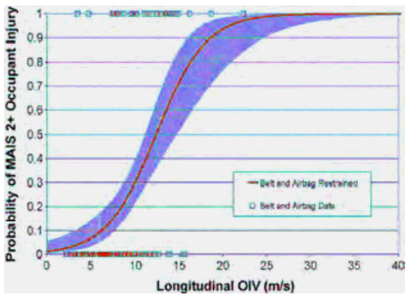

Figure 9. OIV – MAIS 2+ injury risk. (Gabauer & Gabler 2008b)

Kullgren et al. (2008) showed with frontal crash severity data from EDRs, the risk of sustaining an injury for three MAIS levels; MAIS1+, MAIS2+ and MAIS3+. AIS 1 neck injuries account for a large proportion of the AIS1 injuries (Berglund, 2002; Krafft et al., 2002; Malm et al., 2008). The MAIS2+ risk was found to be 20% at a change of velocity of approximately 35 km/h (Figure 10). A comparison with the US data from Gabauer and Gabler (2008b) showed a similar result (Figure 8). This was based on 145 crashes with GM cars in the USA and the risk curves were based on logistic regression, which is different from the method used in the studies conducted by Kullgren et al. (2008). In studies of occupant injury risk with respect to crash severity, it is difficult to avoid the influence of occupant compartment intrusion. Augenstein et al. (2005) showed that AIS3+ intrusion injury percentage was 93% in crashes with change of velocity above 56 km/h. In studies such as Kullgren et al. (2008), major intrusion is included in crashes with high crash severity. The injury risk curve (Figure 10) consequently shifts to the left for high crash severity in the presence of intrusions. There are examples of studies explaining the relationship between injury risk and proportion of intrusion (Thomas et al., 1995; Augenstein et al., 2005; Wood et al., 2007). Figure 11 shows an AIS3+ injury and fatality risk curve calculated with power regression together with the proportion of cases with occupant compartment intrusion (Wood et al., 2007).

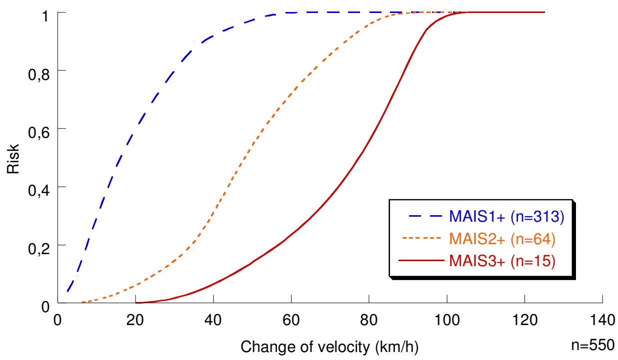

Figure 10. Change of velocity – injury risk.
Source: (Kullgren 2008)

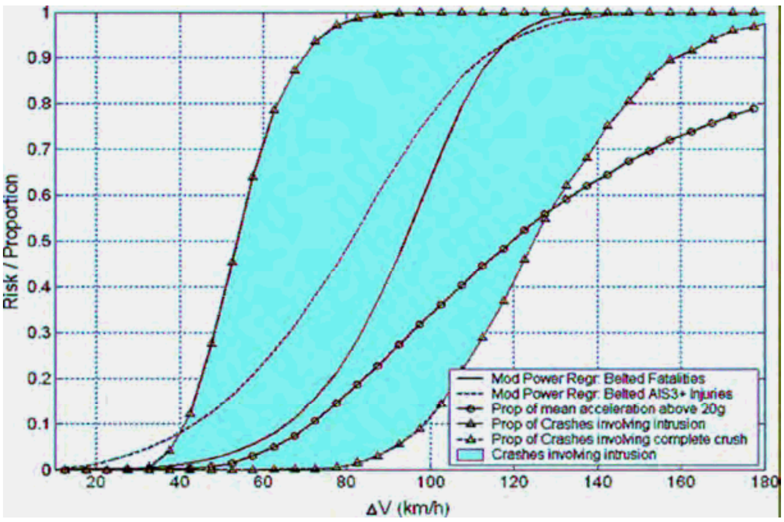

Figure 11. Distributions of onset of intrusion, complete car crush and mean acceleration above 20×*g* compared to real world belted driver AIS3+ and fatality risk functions. Wood et al. (2007).

2.8 COLLISION PARTNERS

2.8.1 Two-vehicle crashes

Two-vehicle crashes constitute 60% of fatalities in personal vehicles in Sweden (SIKA, 2007). In this thesis, the term "collision partner" includes both vehicles and objects beside or near the roadway. In two-vehicle crashes a lot of research has been conducted on compatibility, see for example (Jenefeldt and Thomson, 2004; Thomson, 2004; Faerber, 2005). Besides compatibility issues in vehicle structure, for example front structure stiffness or geometric differences in load paths (Lindquist et al., 2004), another compatibility issue in the road transport system is the variation in curb weight in different vehicle fleets. The discrepancy of curb weight has increased in Sweden and other EU countries (SIKA, 2004). New vehicle segments with lightweight vehicles focusing on low fuel consumption have appeared at the same time as more heavy SUV type vehicles that create an increasing distribution of vehicle curb weight. It is therefore important to adapt the road transport system for these different vehicle types. One of the most difficult compatibility problems to deal with in two-vehicle crashes are frontal crashes with HGVs (Krusper and Thomson, 2008) since the curb mass ratio of a car and an HGV can be up to sixty.

2.8.2 Single-vehicle crashes

Collisions with roadside objects constitute a major problem since they account for between 18% and 42% of all fatalities in Europe (ETSC, 1998; SIKA, 2007). In single-vehicle crashes, it is not obvious how to categorize rigid objects. Extensive work in this area however has been done by Thomson et al. (2006) showing guidelines for road infrastructure on new and existing roads. A rigid object is not necessarily always a hazardous object. It depends on impact speed, distance from roadway, object dimension and impact angle. A rigid guardrail can have excellent crash performance even at high speeds as long as the exit angle is small. For larger impact angles, >20°, the crash severity increases considerably (Ydenius et al., 2001). Thomson et al. (2006) showed however that although the theoretical possibilities can lead to great exit angles, 90% of 82 reconstructed crashes had exit angles below 20°. Their study did not include bendy roads that make the exit angle larger.

2.9 NEED FOR INTERACTION

To achieve the goal of a more sustainable road transport system, there is a need to better understand the integration of vehicles and road design (Rasmussen, 1997). This requires improved knowledge about the crash severity to which car occupants are exposed in vehicles in specific road environments. As a tool in this work, accurate crash severity data from real-world data create possibilities for determining the limit of dose, which ensures harmful levels stay within biological tolerance limits (Glaister, 1978) in different road environments. Occupant injury tolerance derived from real-world data is also an input in the validation of different models such as the SRA model (Linnskog, 2007) or RPS.

There is a need to study the correlation between occupant injury and vehicle crash severity and how crash severity and injury risk varies in different road environments and in collisions with different vehicles and roadside objects. Such a method could be used to evaluate guidelines in the design of a safe road transport system, but also to look at interventions on existing roads.

3 AIMS

The overall aim of this thesis was to study the integration of vehicle and road infrastructure design and to evaluate suitable crash severity parameters to be used in the design of a safe road transport system.

The specific aims were to:

1. Evaluate how various road-related parameters influence crash severity for single and two-vehicle crashes.

2. Study the correlation between pulse duration and injury risk by means of change of velocity, mean and peak acceleration and how the risks are influenced by pulse duration.

3. Present differences in average crash severity and distribution of crash severity depending on collision partner.

4. Study the interaction between occupant injury potential and guardrails.

5. Evaluate occupant injury tolerance guidelines to be used in the design of a safe road transport system.

4 MATERIALS AND METHODS

Studies I –III are retrospective studies of car crashes investigated in-depth in Sweden. Approximately 260 000 vehicles have been equipped with a mechanical EDR called a crash pulse recorder (CPR) since the start of the project from 1992 until 2009. The inclusion criterion was a target vehicle repair cost exceeding 50 000 SEK (approximately 5 000 EUR). All rear-end crashes were included, irrespective of repair cost. Rollover crashes were however excluded in vehicles with EDRs. Vehicles from which the EDR data were presented were only frontal impacts or rear end crashes within a ± 30º impact angle**.** The EDRs were mounted below one of the front seats. The sampling frequency of the EDR was 1000 Hz and the acceleration time history was filtered with a CFC60 filter. Vehicle collision partners had no restrictions regarding impact angles. Questionnaires regarding accident circumstances and occupant injuries were sent out to the drivers within a month. Injury data were also collected from insurance claims adjusters. Information about crash type and crash scene was collected from police reports and accident claims.

4.1 STUDY I

Study I is one of two studies in this thesis with the aim of analyzing the influence of road design, road side objects and car types on crash severity using data from onboard EDRs.

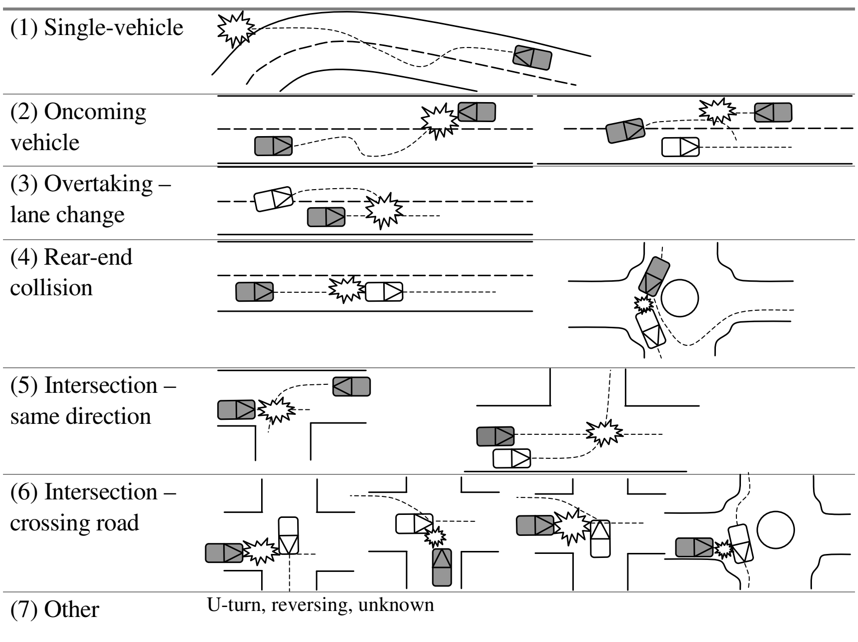

Figure 12. Crash types divided according to SIKA. Dark vehicle with measured crash severity.

Study I provides crash severity data for various types of road design and describes in which road design the most severe frontal crashes occur. Study I was based on 422 frontal vehicle crashes that occurred in Sweden during 1992–2006. Both two-vehicle crashes and single-vehicle crashes were included. The acceleration time history was measured in 29 vehicle models. The distributions of various crash pulse characteristics were presented for some road-related parameters. These parameters were posted speed limit, land use, surface friction and crash types, see Figure 12. The crash types were categorized according to a procedure used by SIKA, the responsible authority for Swedish traffic statistics (Larsson, 2006; SIKA, 2007).

The crash severity figures were presented with a 95% confidence limit and a 95 % significant test (t-test) was applied to all data to verify significant differences.

4.2 STUDY II

This retrospective study was conducted with frontal vehicle crashes that occurred in Sweden during 1992–2007. Two-vehicle crashes, frontal and rear, as well as frontal single-vehicle crashes were included. The crash severity, mean- and peak-acceleration and change of velocity were measured in 544 crashes with 29 vehicle models fitted with onboard CPRs.

Average crash severity was evaluated for different categories based on the type of vehicle or object the vehicle collided with. Three main categories were identified; frontal two-vehicle crashes, single-vehicle crashes and rear-end crashes. Frontal single-vehicle crashes were divided into two subcategories: crashes with deformable and rigid objects. In two-vehicle crashes, the opposite vehicles were categorized in six passenger car size categories with HGV/buses in a separate category. To explore the difference in crash severity distribution between categories, the number of crashes above a specific level in crash severity was studied. For frontal two-vehicle crashes and for rear-end crashes, the level was chosen to represent 95% and 90% of the crashes, respectively. Average mean acceleration and change of velocity for each category were compared. Statistical differences between categories were calculated using t-tests and Mann-Whitney tests.

4.3 STUDY III

Frontal crashes from a car fleet comprising 29 vehicle models, with onboard CPRs were analyzed in this study. The study consists of 578 front seat occupants in 448 crashes. Front seat occupant injuries were coded according to AIS 2005 (AAAM, 2005) from hospital records and self-reported information given in the claims reports and questionnaires.

The first step in the method to calculate injury risk was to divide crash severity measurements into fixed intervals. Injury risk was calculated and plotted as the proportion of injured in each interval. The observations were connected by a “smooth curve fit” using software from Kaleidagraph (2000).

The calculated crash pulse characteristics were mean acceleration, peak acceleration, change of velocity and pulse duration. For change of velocity, mean and peak acceleration, injury risk curves were calculated for front seat occupants. Plot diagrams were used to show the correlation between two severity parameters at the time with the intention of studying the influence on injury risk of various parameters.

Both predictivity analysis and simple logistic regressions were used to further evaluate the influence on injury risk for various crash pulse characteristics and also the correlation between occupant age and injury risk. An analysis of the differences in median age was conducted on both injury groups (MAIS2+ and MAIS 3+ injuries) in relation to uninjured occupants or occupants with lower injury level by using the independent-samples median test.

4.4 STUDY IV

Crash tests were conducted with three kinds of guardrails at two impact angles and two test speeds to analyze the influence of different guardrail types on various parameters. The parameters analyzed in this study were vehicle mean and peak acceleration, change of velocity, accident severity index (ASI), pulse duration, dummy head measurements, guardrail deflection and vehicle exit speeds. Two test set-ups were chosen; one 45 degree test at 80 km/h and one 20 degree test at 110 km/h. The 45 degree test was chosen to represent a crash condition more severe than the existing 20 degree test used for European guardrail standard EN1317 (CEN, 1998b). The tested guardrails were rigid concrete guardrail, wire rope guardrail and semi rigid W-beam guardrail. The vehicles were instrumented with several accelerometers. However, in the comparisons, measurements from the accelerometer at the centre of gravity were used. The driver dummy was a Hybrid III with head accelerometers. The crash test results were compared with the real-world crash data presented in paper II on the same kinds of guardrails.

5 RESULTS

5.1 STUDY I

Together with study II, study I provide measured crash severity data for crashes in different road environments and different collision partners. Study I focuses on crash type, speed limit and road friction. The crash severity in two-vehicle crashes related to land use was higher in rural areas than in urban areas. The most severe crash type on rural roads was two-vehicle crashes with oncoming vehicles. Oncoming vehicle crashes showed a higher crash severity than intersection crashes, rear end crashes or single-vehicle crashes. In oncoming vehicle crashes (Figure 12(2)), the average change of velocity was 32 km/h and the average mean acceleration 8.6 g. In the second most severe crash type, intersection crashes in the same direction (Figure 12(5)), the average change of velocity and mean acceleration were 22 km/h and 6.4 g, respectively (Figure 13).

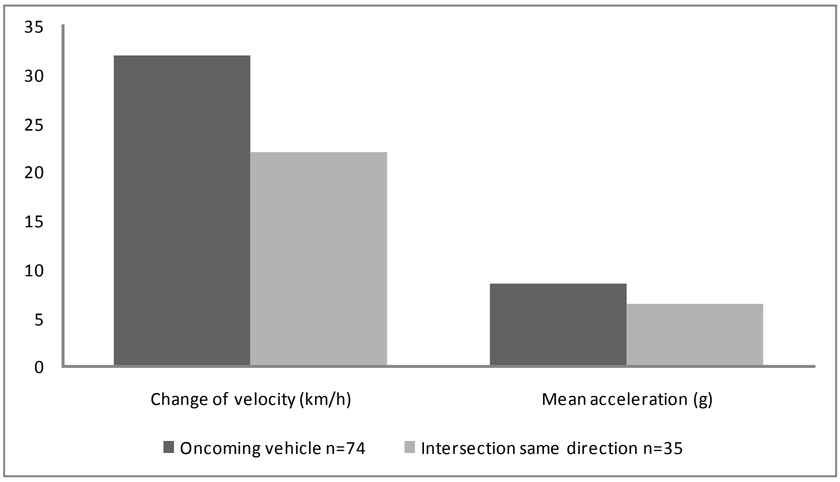

Figure 13. Measured change of velocity and mean acceleration in frontal crashes for the two most severe crash types.

The average crash severity in crashes on roads with different posted speed limits (50, 70, 90 and 110 km/h) was largest on roads with a speed limit of 90 km/h. The average change of velocity was 24 km/h and the average mean acceleration was 6.5 g. The change of velocity was lower on both 50 km/h roads and 70 km/h roads compared to 90 km/h roads. The average change of velocity was higher (8 km/h) on dry roads compared to snowy and icy roads in single-vehicle crashes.

This study shows that the average impact severity of crashes depends not only on the struck object itself, but also on the traffic environment in which the crash occurs. In the development of new safety technologies, real-world crash severity data are valuable as input in attempts to predict the safety benefit of these technologies in various road traffic designs.

5.2 STUDY II

While Study I focused on crash severity for various parameters associated with road design and its surroundings, study II focused on the struck object, in two-vehicle crashes, as well as in single-vehicle crashes.

The crash severity in frontal two-vehicle crashes was significantly higher than in all single-vehicle crashes. The average change of velocity and mean acceleration was lower for the category 'single-vehicle crashes with deformable object' than for 'single-vehicle crashes with rigid roadside object'.

The highest average change of velocity and mean acceleration were found in frontal two-vehicle crashes (19 km/h and 6.4 g) and single-vehicle crashes into rigid objects (21 km/h, 5.8 g). The lowest crash severity in frontal impacts was found in the category 'single-vehicle crashes into deformable objects' (15 km/h, 4.0 g). In single-vehicle crashes, there was a 45% higher mean acceleration in collisions with rigid roadside objects compared to collisions with deformable objects. No crashes with deformable objects occurred with a mean acceleration higher than 9 g. Only 8% of the crashes with deformable objects had a higher mean acceleration than the geometric average mean acceleration for crashes with rigid roadside objects.

In 2% of the crashes with "superminis" and "small family cars", the change of velocity was larger than 45 km/m, while in 22% of the crashes with HGVs, the change of velocity exceeded 45 km/h.

5.3 STUDY III

Study III provides risk calculations that link the crash severity data measured in studies II and I to occupant injury risk. Study III shows that the change of velocity, commonly used as a severity parameter, can be successfully complemented with mean acceleration.

95 % of the MAIS2+ injuries occurred at durations between 88 ms and 141 ms. There are no MAIS2+ injuries at durations above 158 ms. The distribution of crashes pulse duration was between 40 and 250 ms (Figure 14). It was found that the risk of MAIS2+ injuries for duration (Figure 15) does not increase continuously as for the other parameters studied (Figures 16 and 17). The correlation between duration and change of velocity had a correlation coefficient (r^2) of 0.26 (Figure 19). The crash pulse duration was plotted versus mean acceleration in Figure 18 with a correlation coefficient of 0.07.

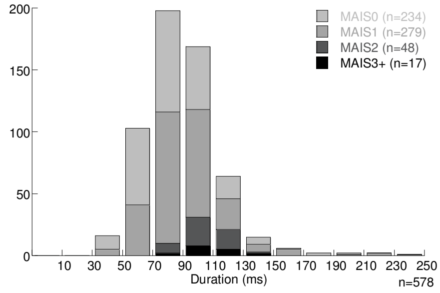

Figure 14. Distribution of injuries versus duration.

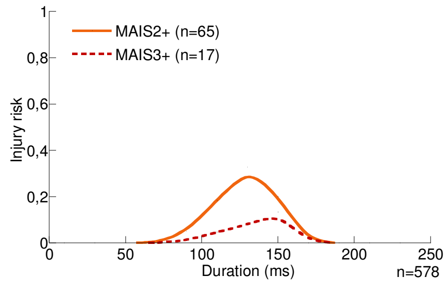

Figure 15. Injury risk versus duration.

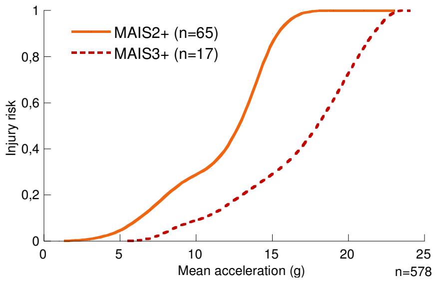

Figure 16. Injury risk vs. mean acceleration.

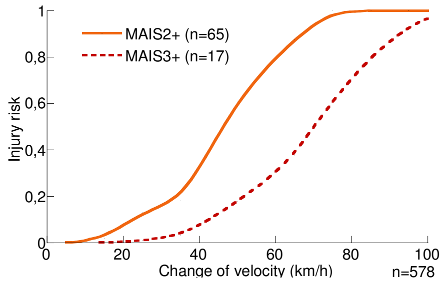

Figure 17. Injury risk versus change of velocity.

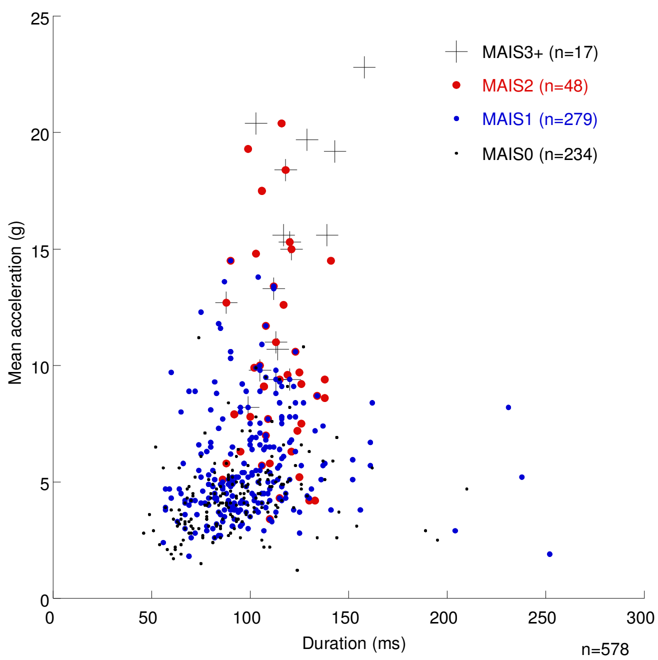

Figure 18. Correlation between duration and mean acceleration.

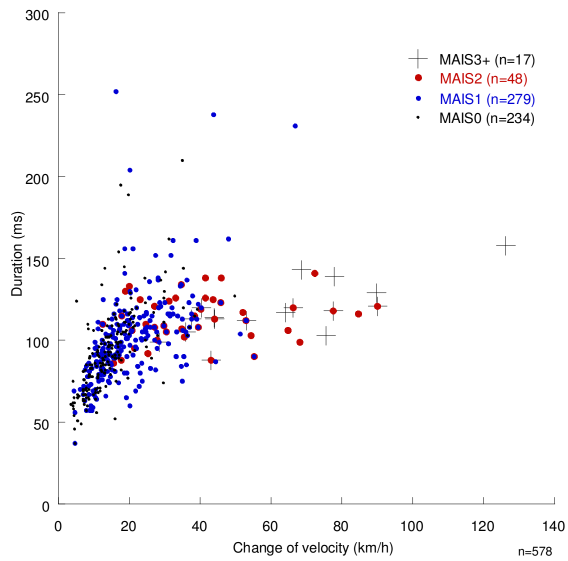

Figure 19. Correlation between change of velocity and duration.

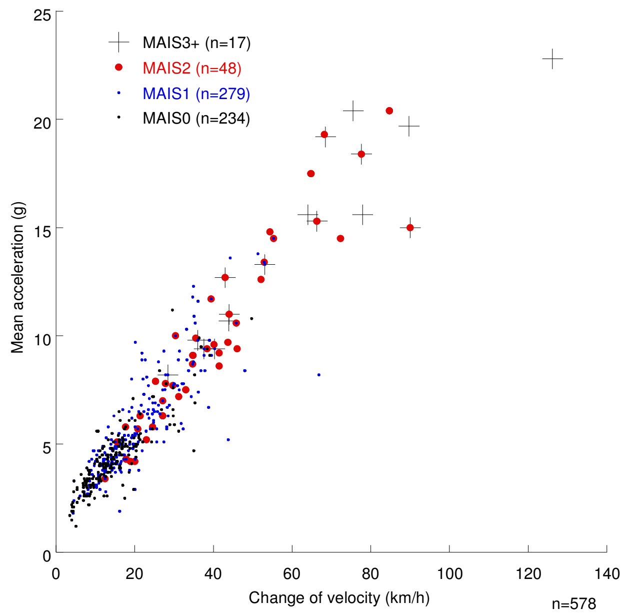

Figure 20. Correlation between change of velocity and mean acceleration

Change of velocity and mean acceleration were found to be well correlated with injury (Figures 16 and 17). They were also found to be well correlated with each other (Figure 20), with a correlation coefficient of 0.88.

Various statistical analyses were conducted, predictivity of injury for the different parameters, simple logistic regression to determine the odds ratio (OR) of each parameter and difference in risk ratio for occupant age above and below age 60. The predictivity analysis showed that duration did not predict MAIS2+ injuries to the same extent as the other parameters (Table 1).

Table 1. Positive and negative predictive values for occupants with MAIS2+ injuries.

Crash pulse characteristics	Threshold*	$P_{specificity}$	Proportion of occupants **with** MAIS2+ injuries above threshold (Positive Predictive Value)	Proportion of occupants **without** MAIS2+ injuries below threshold (Negative Predictive Value)
	$P_{sensitivity}$ =0.85			
ΔV	24.6 km/h	0.81	55/155 = 35 % ± 8%	413/423 = 98% ± 1%
Mean acc.	6.3 g	0.78	55/170 = 32 % ± 7%	398/408 = 98% ± 2%
Peak acc.	16.7 g	0.80	55/156 = 35 % ± 7%	412/422 = 98% ± 1%
Duration	100 ms	0.61	55/256 = 21 % ± 5%	312/322 = 97% ± 2%

*The threshold was chosen as the level for each crash pulse characteristics where the proportion of occupants with 85% MAIS2+ injuries was 55/65. This means that the sensitivity chosen was 0.85.

Simple logistic regression showed that duration had lower influence on injury risk than change of velocity, mean acceleration and peak acceleration (Table 2). The odds ratio (OR) for duration was significantly lower than for change of velocity and mean and peak acceleration. However, the OR was not significantly different for change of velocity, mean acceleration and peak acceleration. Occupant age had significantly lower influence on injury risk than change of velocity, mean acceleration and peak acceleration for both MAIS2+ and MAIS3+ injuries ($p < 0.05$) (Table 2). It was found that occupants older than 60 years had 62% higher risk for MAIS2+ injury compared with those younger than 60 ($p < 0.05$) (Table 3).

Table 2. Odds ratio (OR) for different parameters.

	MAIS2+			
	n	e^B (OR)	95% Wald CI	p
Delta-V	578	5.572	3.931-7.898	<0.0005
Mean acc.	578	4.722	3.452-6.459	<0.0005
Peak acc.	578	4.562	3.467-6.003	<0.0005
Duration	578	1.745	1.383-2.202	<0.0005
Age	563	1.348	1.034-1.757	0.027
	MAIS3+			
	n	e^B (OR)	95% Wald CI	p
Delta-V	578	3.754	2.901-4.858	<0.0005
Mean acc.	578	3.799	2.782-5.187	<0.0005
Peak acc.	578	4.232	3.104-5.777	<0.0005
Duration	578	1.675	1.193-2.351	0.003
Age	563	1.644	1.069-2.528	0.024

Table 3. Risk ratios for occupants above and below 60 years age.

	n	e^B (RR)	95% Wald CI	p
	MAIS2+			
Age 0-59	416	1		
Age 60+	147	1.617	1.016-2.574	0.043

5.4 STUDY IV

The last study was conducted with a series of crash tests into three types of roadside guardrails often used as a solution to avoid hazardous areas or collision partners. In collisions with impact angles smaller than 20º, the difference in crash severity between the different types of guardrail could be expected to be limited. Figure 21 shows the difference in resultant mean acceleration for the three types of guardrail.

The resultant mean acceleration in the 20° tests was lowest for the cable- and W-beam guardrails (3.6 g and 3.5 g, respectively) compared to the concrete guardrail (7.2 g). In the 20° test, the W-beam guardrail and cable guardrail had ASI values of 0.8 and 0.7, respectively, which pass the A-class level (Table 4), while the concrete guardrail had an ASI of 1.2, corresponding to the B-class level. The A-class level, ASI below 1.0, represents the lowest loadings on the car. In the 20° test, the crash pulse duration was 84 ms for the concrete guardrail and 308 ms and 419 ms for the W-beam guardrail and the cable guardrail, respectively. There was no deflection of the concrete guardrail while the W-beam guardrail and cable-guardrail had 0.5m and 1m deflection, respectively.

Table 4. EN 1317 accident severity classes.

Class	ASI
A	ASI ≤ 1.0
B	1.0 < ASI ≤ 1.4
C	1.4 < ASI ≤ 1.9

In the 45° test, the resultant mean acceleration was 17.0 g for the concrete guardrail, while it was 5.5 g and 3.5 g for the semi-rigid W-beam guardrail and cable guardrail, respectively. The ASI values in the 45° test show that the only guardrail that failed the ASI criteria was the concrete guardrail in the 45° test (ASI above 1.9), while both the W-beam and cable guardrails had an ASI value well below 1.0. The crash pulse duration in the 45° test into the concrete guardrail was 153 ms compared with the other two guardrail types, which both had durations of 431 ms. The concrete guardrail had virtually no deflection, whereas the cable guardrail had a 3.5 m deflection in the 45° test.

A small impact angle into a longitudinal guardrail is in general expected to generate less impact forces than for a larger impact angle. The increase in mean acceleration was calculated from Figure 21. The concrete guardrail had the largest change of crash severity between the two test angles, with a 136% increase in resultant mean acceleration, while the W-beam and cable guardrail tests showed a 22% and a (-3%) change of mean acceleration, respectively. This demonstrates the forgiving properties of deformable guardrails in comparison to rigid ones.

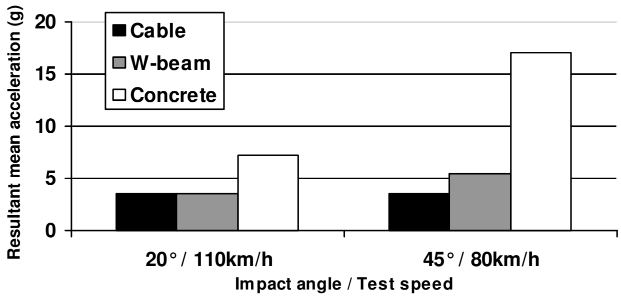

Figure 21. Resultant mean acceleration measured in guardrail crash test.

6 DISCUSSION

Casualties in the road transport system are still one of the major public health problems in society. Although impressive progress has been achieved in the area of road transport safety, the numbers of occupant injuries and fatalities do not decrease at the rate that society desires.

With Vision Zero (Tingvall and Lie, 1996) and the SRA model (Linnskog, 2007), the Swedish road administration has established an approach whereby the road transport system should be designed for human physical and mental limitations. To realize this vision, there is a need for better knowledge about injury tolerances for different traffic elements and crashes. The knowledge to date is not sufficient to describe the level of crash severity that should not be exceeded in order to prohibit occupant injuries. To be able to gain knowledge regarding crash severity in vehicle crashes, studies of real-world crashes are important. A prerequisite for such studies are data from onboard crash recorders or EDRs that can measure crash severity parameters with sufficient accuracy. With crash severity limits adapted to occupant injury tolerance, it will be helpful in the determination of more effective safety measures in vehicles or in the road environment to prevent injuries and fatalities.

This thesis adds knowledge on the correlation between crash severity and injury that can be used as input in the design of a safe road transport system. Studies II and I show significant differences in crash severity depending on road environment and collision partner. With the results from study III, the injury risk can be determined from the crash severity measured in studies II and I. Study IV shows large differences in crash severity and pulse duration with different guardrails. The results from study III show that there is no increase in injury risk if the crash pulse duration exceeds common values (> 120 ms). These findings for injury risk and crash severity can be used to formulate guidelines for the design of a safe road transport system as well as for the evaluation of many preventive technologies. Examples of preventive technologies are guardrails aimed at distributing the crash energy during a longer time or Autonomous Emergency Braking systems (AEB) aimed at reducing the impact speed or avoiding crashes.

6.1 SYSTEMS APPROACH

Traditionally, different stakeholders of the road transport system have devised their own safety preventive actions on an individual basis. The cooperation between road and car designers has been limited (Lum and Reagan, 1995). During the 1980s and 1990s, while the vehicle industry made great progress in the crashworthiness of cars, road designers did not prioritize safety to the same extent. Although safety measures were achieved (Garber and Graham, 1990; de Leur et al., 1994; Corben et al., 1997; Harwood et al., 2003), the consequences of changes to road design were not properly adapted to vehicle crashworthiness (Delaney et al., 2002).

In large technical systems, for example the aviation safety, a systems approach was developed to improve safety. The idea was to make all improvements before the accident occurred, which requires a holistic view of the problem. That was one key to the successful evolution towards the safest method of travel, the airline. Vision Zero is built on a similar strategy. The individual road user cannot take full responsibility for the safety of the road transport system. To be able to distribute the areas of responsibility between the different stakeholders, the road traffic system needs to be treated as a coherent flow of events showing how each event is related to each other (Figure 4). EuroRAP, which adopts a systems approach in the identification of hazardous roads and is based on human tolerances in crashes, provides one important tool. EuroRAP focuses on various dangerous road design features and estimates each individual risk factor in a list of risks (stars 1-4) for the whole road infrastructure. Stigson (2009a) showed that change of velocity and mean acceleration were found to be lower in a crash on 4 star rated roads than in crashes on roads with 1-3 stars. However, the EuroRAP model is not always valid and needs to be reviewed.

6.2 DOSE-RESPONSE

With the dose-response model, the injury-preventing effects of safety measures that influence injury risk, crash severity or crash exposure, can be evaluated (Kullgren, 2008). One conclusion from study I is that real-world crash severity data from retrospective studies is a prerequisite to make better evaluations of the effectiveness of new road designs. In the dose-response model, a dose is expected to give a response in terms of vehicle occupant injuries. The external dose could be the relative velocity between two vehicles or the impact speed in single-vehicle crashes. But most often, the dose is expressed as the change of velocity that the vehicle is exposed to during the crash. Study III shows that the three parameters, change of velocity, mean acceleration and peak acceleration all predict the risk of injury and can be used in the dose-response model. The dose-response model can also be used in analyses using more than one dose parameter at the time to show how the injury outcome is influenced by two parameters changed individually (Study III). For example, with equal changes of velocity, parameters like acceleration can be lowered in collisions if objects are designed for longer crash pulse duration. This is important because one result from study III is that a higher change of velocity can give an acceptable low injury risk if the impact is distributed over a longer time duration, resulting in lower acceleration forces, which agrees with the findings of Mills and Harding (1983) and Wågström et al. (2005).

The response is the level of injury that the occupants sustain as a consequence of the force loaded onto the vehicle in a crash. The risk of an injury from a given dose is expressed on injury risk curves. Injury risk curves such as those presented in study III and other studies such as Ydenius et al. (2001), Kullgren (2008) and Gabauer et al. (2008a, 2008b) can be used in the dose-response model. Study III concluded that acceleration should preferably be used in the safe design of vehicles and roadside objects due to the finding that long pulse duration does not increase injury risk.

The dose used in this thesis is measured in the car and not the forces directly acting on the occupant body. The force applied on the car passes through a number of filters before acting on the occupant body. These filters are for example differences in restraint systems, seating position and design/shape of the interior. The expression *filter* may give the impression that the forces transferred from the vehicle to the occupant body are always reduced, but this is not the case if for example the seat belt is slack and the occupant not is attached to the vehicle during the first part of the crash phase.

Therefore occupant injury tolerance limits cannot be obtained with this data (unless a crash reconstruction is used). However, limits on crash severity that should not be exceeded in order to avoid injuries can be used as design guidelines.

Some caution has to be taken regarding the generalization of injury risk curves in this thesis due to the fact that lots of factors influence injury risk. Several studies such as Ydenius (2001) and Bédard et al. (2002) have shown examples of factors, such as age, gender, occupant position, presence of airbag, that more or less influence injury outcome. If the road transport system should be adjusted to occupant injury tolerance, then it is not the average occupant tolerance that should serve as guideline. The most appropriate adjustment to occupant injury should be for the most vulnerable occupants. In general, crashes with older occupants are at greater risk of injury. For some injury types, women have a greater risk of injury than men.

6.3 CRASH SEVERITY

6.3.1 Reduction of crash severity

The dose-response model (Figure 5) shows that reduction of crash severity (a shift of the crash distribution curve to the left) is one way to reduce the number of injured. The usual way to reduce loadings on occupants is accomplished through vehicle crashworthiness and there is still potential to evolve better vehicle structures (Wågström et al., 2005) and various types of passive safety systems (Kullgren, 2008). An example of a change in vehicle structure is the use of pressurized frontal longitudinal members. Mathematical simulations show a significant reduction of occupant loadings (Pipkorn, 2009). Changes in the shape of frontal side member cross-section was shown to generate 91% increase in energy absorbing capacity for an impact at 48 km/h (Giess and Tomas, 1998).

Adjustments in road design however also have a large influence on reducing crash severity. Study I has shown that measures such as the use of guardrails compared to unprotected roadside areas gives a reduction of crash severity of approximately 7 km/h or 1.2g. This corresponds approximately to a 10–15% decrease in MAIS2+ injuries (Study III). A systematic literature of 32 studies that have evaluated the safety effect of guardrails reduced both accident rate and accident severity (Elvik, 1995).

Road design is important since it helps avoid the crash (event 4) and reduce the crash severity (events 5-6) (Figure 4). In these events, speed promoting measures (for example speed limits and speed cameras) and the crashworthiness of roadside hardware and other objects beside the road have an effect on both the change of velocity and vehicle acceleration. Impact speed is to a large extent decided by the posted speed limit. One of the results from study I was that the crash severity was 4.6 km/h lower on roads with 70km/h posted speed limit compared to 90 km/h roads. Applied to the injury risk curve in study III, the decrease in MAIS2+ injury risk is approximately 6–11%. The same crash severity applied to Evans' (1994b) calculations of injury probability on belted drivers shows a 3–6% decrease in injury risk. A comparable reduction of injury risk was presented by Buzeman (1998) who found a 13% reduction of serious injuries by changing the impact speed from 90 km/h to 80 km/h. Increasing the speed limit is shown to generate an increasing risk of injury as shown by several studies (Nilsson, 1982; Garber and Graham, 1990; Joksch, 1993; Renski et al., 1999; Nilsson, 2004). Vision Zero clearly points out that no single factor has as great an impact on safety as speed. Study I indicated however a lower average mean acceleration and change of velocity on roads with posted speed limits of 110km/h than on roads with limits of 90km/h. This result is supported and further explained by Stigson et al. (2009a), who found that on roads with good safety ratings crash severity were lower with a speed limit of 110km/h compared to 90km/h. On the other hand crash severity on roads with poor safety rating were higher with a speed limit of 110km/h compared to 90km/h. The reason for that difference is mainly because, in contrast to roads with poor safety ratings, a majority of the 110km/h roads with good safety ratings have mid barrier which avoids severe two-vehicle head on crashes. The study by Renski et al. (1999) showed no significant effect on crash severity when increasing the speed limit from 65 to 70 mph on Interstate highways, but an effect was seen for an increase from 55 to 65 mph. One explanation may be that the road design has an influence on impact severity. High speed roads may have separated lanes over a longer portion of their lengths thereby avoiding high speed frontal crashes and roadside guardrails that protect from hazardous areas beside the road. The results from studies III and I show that it is possible to determine injury risk with respect to speed limit but also show the importance of further studies of injury risk with road design as an additional risk parameter.

Besides less stiff single vehicle objects (study II) or changes in vehicle structure (Wågström et al., 2005; Pipkorn, 2009), which influence crash severity, a smart interior safety system can contribute to distributing the occupant ride-down acceleration over a longer time. This is important because in the real world there is great variation in vehicle size and future demands on fuel economy will force smaller vehicles to be made. The smallest vehicles with limited space for deformation structure are dependent on interior safety to achieve an acceptable safety level. The interior safety also contributes to achieving better protection for the more vulnerable occupants, for example older people, children or females.

The upper limit of crash severity from which a vehicle can protect its occupants from serious injuries or worse is not fully known. This knowledge is important because it defines the responsibility between the parties involved in the road traffic system. The road designer must know up to what crash severity the vehicle can handle and have the responsibility of designing a road adjusted to that level. The results from study III show an approximate 50% risk of MAIS3+ injuries for a change of velocity of 70 km/h. This result was from a mixed vehicle fleet of cars with various safety levels. A sustainable road design must also allow occupants to survive in cars with moderate crashworthiness. Other results from simulations show that driver protection may allow impact speeds up to 80 km/h (Pipkorn et al., 2005).

During the last decade, new active vehicle safety systems like ESC have appeared which have had a greater effect on reducing crashes with injured occupants (Aga and Okada, 2003; Dang, 2004; Farmer, 2004; Lie et al., 2004; Bahouth, 2005; Ferguson, 2007) than previous systems like ABS (Kullgren et al., 1994; Farmer, 2001). ESC both avoids crashes and reduces impact speed during skidding. The reduction of speed prior to impact is also the purpose of the latest radar-based automatic emergency braking

(AEB) systems. AEB can reduce speeds by 10–20 km/h (Coelingh et al., 2007), resulting in a large reduction in kinetic energy and directly influencing crash severity. The benefit would be even greater if HGVs and buses were equipped with such a system because of the larger crash severity caused by these vehicle types (Strandroth, 2009). Today, an oncoming frontal crash with an HGV on a 70 km/h road is considered un-survivable, but with help of AEB, such crashes could be survivable. Results from study III, Kullgren (2008) and Krafft et al. (2009) show that there is a potential for shifting the crash distribution curve to the left with ESC and collision mitigation systems. To be able to analyze the effectiveness of new systems like AEB, the dose-response model can be used successfully (Kullgren, 2008). With a reduced impact speed of 20 km/h and with the assumption that the reduction in the change of velocity would be 50% of the reduced travel speed, Kullgren (2008) showed a reduction in the number of MAIS2+ injuries of 44 % using crashes from the same database as the one used in this thesis. If the reduction in impact speed could be extended even up to 40 km/h, which is not an unlikely development, the reduction in MAIS2+ injuries could be up to 70 % (Kullgren, 2008). Such an impact on injury outcome is difficult to predict without using the dose-response approach. This technology is rather new and complicated and a crucial problem for the car industry to achieve is the reliable detection of critical situations and of various objects and vehicles.

In single-vehicle crashes, there was a significantly higher crash severity found in study I on dry roads compared to wet and icy roads. Even though slippery roads give less possibility for braking before impact, the crash severity in single-vehicle crashes on icy roads was 35% lower (Study I) than on dry roads. One part of the explanation is from speed measurements on Swedish 90 km/h roads, which according to Öberg (1994) showed that driving speed on average is reduced in winter conditions with ice or hard-packed snow on the road surface by typically 6–10 km/h. In his study, friction was also measured. In terms of braking distance, he shows that the lower friction was not compensated by a corresponding reduction of speed. Since the reduced speed in wintertime did not compensate for the measured lowering friction values, it does however not fully explain the difference in crash severity. Another reason for lower impact speed during wintertime in Sweden is the presence of snow beside the road that lowers the vehicle acceleration in crashes. The lower severity figures for wet roads can also partly be explained in a similar way because crashes in wintertime often occurred on wet roads. It is however not only the crash severity which is an important concern with different friction. The crash type varies with respect to season. A study of fatal vehicle crashes showed that in two-vehicle crashes the oncoming vehicle was struck from the side in approximately 50% of the crashes in wintertime compared to 3% on dry roads (SRA, 2005).

6.3.2 Quality of crash severity data

One major purpose of measuring crash severity is to estimate the risk of injury. The quality of injury risk estimations however depends much on the accuracy of crash severity. The effect of errors in change of velocity estimation on risk calculation has been shown by Funk et al. (2008) and Kullgren et al. (1998). Funk et al. (2008) analyzed 228 NASS single event crashes and showed that the effect on injury risk curves was substantial. The estimation of crash severity from calculation programs (Lenard et al., 1998; Gabler et al., 2004) has larger errors compared with EDR measures (Kullgren, 1998). The estimation of change of velocity is mostly underestimated and can be as large as 10–20% (Dang, 2004; Farmer, 2004; Lie et al., 2004). Crash reconstruction programs such as CRASH3 are commonly used to estimate crash severity in collisions with roadside objects. The difference between actual and estimated change of velocity is likely to be even larger when all impact directions and severities are considered (Lenard et al., 1998; Gabler et al., 2004). The importance of measuring the change of velocity with EDRs is supported by Gabauer et al. (2004) who exemplify the magnitude of estimation errors by comparing change of velocity estimations from WinSmash in an analysis of 65 single-vehicle crashes from NASS/CDS with EDRs. These results showed a 20% underestimation from WinSmash. All methods used to estimate change of velocity and EES have a limited accuracy that further clouds the degree of comparability. The implications of combining different methods for calculating change of velocity need to be better understood and it is likely that new methods are needed to further increase the accuracy.

In recent years, EDRs (Event Data Recorders) have appeared in several projects, which are also capable of measuring acceleration-based parameters directly in the car. There are still problems to address with EDRs. Studies by Ydenius (2002) and study III show that crash pulses in single-vehicle crashes can exceed 230 ms, which is quite far from the usual laboratory crash pulse. Some EDRs are not capable of recording such long crash pulses (Niehoff et al., 2005). The hardware capacity in some EDRs also limits the sampling frequencies and this will most likely lead to an underestimation of the measured crash pulse.

Although EDRs are expected to increase the quality of crash investigations, these are not devices without their disadvantages (Gabler et al., 2003). EDRs are still quite expensive. Problems or imperfections with EDRs like those below can however be solved:

- Insufficient recording time
- Missing data below trigger point
- Inability to record multiple events
- Lack of ability to measure in more than one direction.

The crash severity data in this study were from CPRs with a systematic error of 6–9%. Due to a trigger level of 2–5g, there is an underestimation of the crash severity measurement.

The findings in this thesis clearly show the benefits of using EDRs in real-world crash analysis. It would therefore be desirable to increase the use of EDR data in order to obtain better knowledge of the correlation between crash severity and injury outcome. Although EDRs already exist in several makes of vehicle, there are still too few databases allowing an analysis of occupant injury risk.

6.3.3 Crash severity parameters & injury risk

The crash severity parameters most often used in real-world vehicle safety research are change of velocity and EES (Energy Equivalent Speed), but acceleration has also been appearing more often in the last decade. EES assesses the work done in crushing the car structure. In a vehicle collision where the vehicle comes to rest, these two parameters show similar values, but for impacts with final velocity $\neq 0$, as in glance-off crashes, they can be quite different. Differences in change of velocity and EES were exemplified by Ross et al. (1998) and Berg et al. (1998). Ross et al. (1998) show that a change of velocity from 50 km/h to 30 km/h, gives a larger difference in kinetic energy, and therefore an overestimation of EES, compared to 20km/h to rest, although the change of velocity is the same. The deficiency with using change of velocity is the different estimation result from existing methods, rather than shortage in injury prediction. Study III has shown that change of velocity, mean acceleration and peak acceleration all predict injury. In studies I, II and III, change of velocity is measured with EDRs that increase accuracy and avoid any discrepancy due to different crash modes and crash types which is inevitable in crash severity estimations with software programs.

The acceleration pulse gives, in addition to change of velocity, the possibility of analyzing the influence of mean and peak acceleration as well as shape of pulse and duration on injury risk. The mean acceleration and peak acceleration are qualified as important parameters to consider when studying crashes with a large variation in duration. To be able to design cars and roadside objects, it is therefore necessary to use acceleration-based parameters to achieve desirable crash performance. This is one conclusion from study III.

Buzeman et al. (1998) claim that change of velocity is the best predictor of injury because it reflects both acceleration and intrusion, since for an equal change of velocity a soft structure will cause a low acceleration but higher intrusion, and vice versa. The regression analysis in study III shows no evidence that change of velocity is a better predictor of injury than mean acceleration. Buzeman et al. (1998) point out the weakness with change of velocity because a softer crash with lower acceleration and a lower injury risk can have the same change of velocity as in a stiffer crash with higher acceleration and injury risk.

In study IV, the concrete guardrail tests showed the largest ASI and the more flexible guardrails an ASI below 1.0 in both tests. Studies have been conducted to investigate how the acceleration-based ASI predicts injury (Gabauer and Gabler, 2008b). ASI is normally used in guardrail crash testing. Since ASI includes acceleration data in three dimensions, it can be calculated from 3-axis EDRs. Schram (2006) has shown that the ASI not only is assessable on roadside equipment. He used ASI to explore ways of assessing HGV front underrun protection (FUP) performance for different types of vehicles. His results showed that ASI is predictive of injury (ISS). Gabauer et al. (2008b) showed however that neither ASI nor OIV offers a significant predictive advantage over change of velocity for maximum injury. The limitations in this study were however the small dataset of 45 purely frontal crashes with 96% uninjured or MAIS1 injuries and two occupants with MAIS2+ injuries and short EDR recording times in the range 100–150ms.

Crashes that are more likely to lead to intrusion, for example glance-off crashes, have to some extent been described in vehicle research (Kullgren et al., 1998; Lindquist et al., 2004). A major difference with side and glance-off crashes is that the intrusion speed of an interior surface is larger than in a full frontal crash with identical impact speed. In glance-off collisions or side collisions, the intrusion of the occupant compartment almost starts immediately after impact, which leads to high intrusion velocities. To express injury risk in such crashes, there is a need to investigate crash severity parameters other than change of velocity. Parameters that most likely influence injury risk are amount of intrusion, intrusion speed and occupant contact velocity. Further research is needed to evaluate how the different crash severity parameters correlate with injury during the crash phase when occupant compartment intrusion begins.

To fully understand how injuries occur, there is a need to obtain information about injury risk in crashes occurring in various road environments. The results from this thesis are a first attempt to express crash severity in different road environments. In the dose-response model (Figure 5), reduction of injury risk is one way to decrease the number of injured in the road transport system. The injury risk is therefore a basic tool in the work with integration of road infrastructure and vehicle.

Acceleration has so far not been used to any great extent in injury risk calculations. How acceleration measured in real-world collisions influences injury risk is an important step in forming a strategy where a large change of velocity could be tolerated as long as the acceleration is kept low.

The data from study III have shown a correlation between mean acceleration and injury. Further analysis of the correlation between acceleration and injury can be developed by study duration and vehicle structure deflection and intrusion.

6.3.3.1 Duration

The duration of a crash can be considered to be the result of a specific impact speed and ride-down acceleration. Buzeman et al. (1998) agree with the fact that a stiffer structure will cause larger acceleration and vice versa. This relationship suggests how to move towards the goal of achieving lower acceleration levels through longer pulse duration. For an equal change of velocity in two crashes, as shown in Figure 22, study III shows quite different mean accelerations and consequently different injury risks. This shows the advantage of acceleration as injury predictor.

Study III showed that a longer duration does not lead to increased injury risk. Simulations from PC Crash shows reduction in head and chest loadings for increasing crash pulse duration (Geigl et al., 2003). The analysis of crashes with long duration however needs to be continued. In study III, crashes with the longest pulse duration reached up to 240ms (Figure 22). The change of velocity in these two pulses (Figure 22) is the same but with different mean accelerations. Study III has shown no negative influence of increasing the duration.

A 10% risk of MAIS3+ injuries appears at approximately 9–10g mean acceleration and 40–45 km/h change of velocity. These figures can be compared with the human tolerance to horizontal impacts studied by Glaister (1978). He showed critical limits for both mean acceleration and change of velocity depending on duration. For a given critical limit of change of velocity, the tolerance to acceleration decreases down to a plateau acceleration. This plateau is reached after approximately 0.1 s. The critical level of change of velocity is approximately 32 km/h and the plateau acceleration is 20 g for a three-point belted occupant. This confirms the findings from Study III that duration above common levels (> 120 ms) has limited influence on injury risk. To further analyze injury risk with long pulse duration, it would be possible to study how various distribution patterns of the acceleration pulse shape affect the correlation to injury. These patterns can be identified with a fixed time window moving along the crash pulse. Instead of studying acceleration over the entire pulse length, it would be possible to study the mean acceleration for a limited time window, for example 100 ms. One type of analysis would be to find the maximum mean acceleration of a fixed time window and investigate how the position of that window correlates with injury.

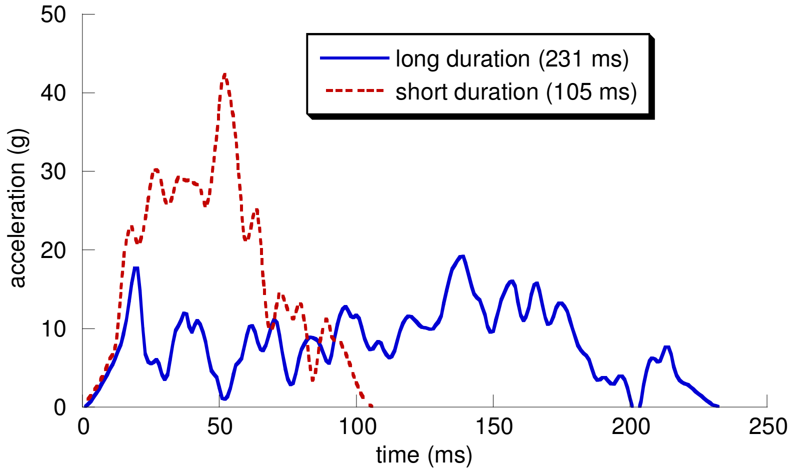

Figure 22. Two crash pulses with same change of velocity and different pulse duration. Source: Study III

6.3.3.2 Intrusion

This study does not consider intrusion as a severity parameter. The vehicle structure can absorb a certain level of energy until the structure starts to collapse. Intrusion causes a rapid increase of injury risk due to increasing contact velocities and crush injuries. Real-life data shows that for example lower limb injuries which have high risk of impairment (Malm et al., 2008), occur for quite moderate intrusion (Thomas et al., 1995). Figure 23 illustrates the area of injury risk, which describes how acceleration and intrusion relate to injury. The influence of intrusion on injury risk needs to be further investigated. An analysis like the one used in this thesis can be helpful to understand the correlation between acceleration, intrusion and injury risk.

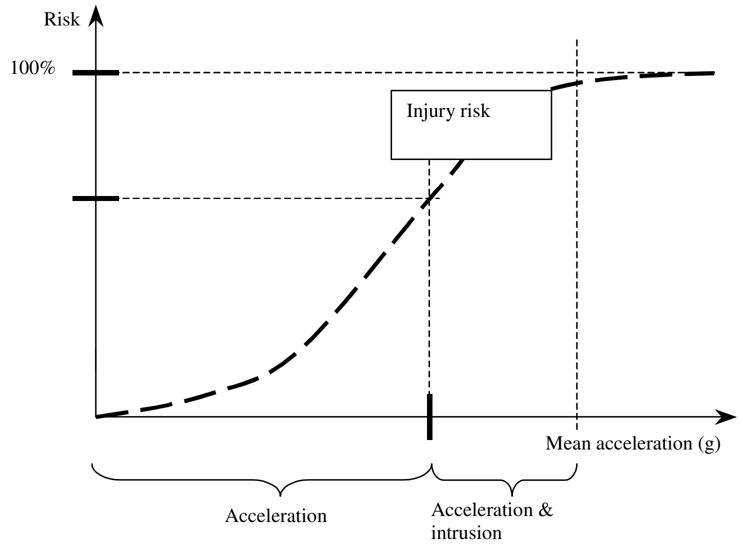

Figure 23. Injury risk versus mean accelaration and intrusion.

An example from a crash test with a frontal, 28% overlap crash, showed no intrusion on the car to the right (Figure 24) while the vehicle on the left received occupant compartment intrusion (Kullgren et al., 1998). The test speed was 58km/h and the mean acceleration for the left vehicle was 3.8g and 3.5g for the right vehicle. This example shows that a weak vehicle structure exposed to a low overlap crash can collapse at relatively low acceleration levels.

Figure 24. Left vehicle with interior intrusion – right vehicle no intrusion. (Kullgren et al., 1998)

6.3.3.3 Quality injury data

One limitation of this study is the relatively small number of cases and vehicle models. The quality however is ensured by medical data from hospital or personal claims inspectors and seat belt use verification through vehicle inspections. Larger databases can give a false feeling of both reliability and validity of data. A relatively small shift can lead to large changes in injury risk for a fixed crash severity. Another aspect of data quality is found in the systematic errors that may lead to shifting the risk curve to the right or left. One example that leads to a left shift of the injury risk curve is the many databases that mostly rely on injury data from the police. The police often overestimate the injury severity (Aptel et al., 1999; Alsop and Langley, 2001; Amoros et al., 2006; Tsui et al., 2009). Another example is the mixture of belted and unbelted occupants due to difficulties with confirming belt usage (Schiff and Cummings, 2004; Guo et al., 2007). The kinds of errors in injury data described above can be quite large and difficult to compensate for.

Most injury data related to road accidents are coded according to AIS and mainly address fatality. If AIS and its derivates are used without understanding that they mainly address fatality, this can lead to the wrong priority of measures. Most traffic accidents lead to non-fatal injuries and few of them are life threatening. Therefore, it is important to also focus on injuries leading to long-term impairment (Kullgren, 1998; Kullgren et al., 2000b). Introducing risk of impairment changes the importance of each injury. This has also been discussed by Håland et al. (1990; 1993), Norin et al. (1997), Morris et al. (2006) and Malm et al. (2008). Knowledge about the risk of injuries leading to long-term impairment with respect to frontal crash severity (Krafft et al., 2002) is very limited. Databases such as the one used in study III could be re-analyzed with respect to impairment as injury outcome. Further analysis in this area is necessary to be able to create a road transport system without fatalities and injuries leading to long-term consequences.

6.4 SAFE ROAD TRANSPORT SYSTEM

Injury tolerance limits are usually expressed in terms of loadings or forces on the body. Tolerance limits to be used as guidelines in the design of a safe road transport system could be expressed in terms of the vehicle response in a crash. Tolerance limits based on vehicle response are also an important tool in studies of the integration of the vehicle and the road infrastructure.

An essential finding is to keep acceleration levels low in a crash (study III). Figure 25 illustrates crash pulses from two impacts with similar changes of velocity but distributed over a different time period, thus having very different mean accelerations. Figure 25 generally shows that even if the crash severity in terms of change of velocity is similar, a crash with a shorter duration gives higher acceleration levels and an expected increase of injury risk. Therefore low acceleration levels should permeate the design of road infrastructure. Lower acceleration and crash severity in general, can be obtained in a crash both with road and vehicle measures. The crash severity, both mean acceleration and change of velocity of the vehicle can be reduced with adjusted posted speed limits adapted to the ability of the road infrastructure to not exceed injury tolerance limits. Supporting systems in the vehicle also have the potential to reduce crash severity. AEB systems apply the brakes prior to impact but also ESC systems reduce the speed in skidding situations. Both ESC and AEB systems monitor the vehicle without any need for driver interference. Especially the design of roadside elements has the potential to affect the acceleration level in a crash.

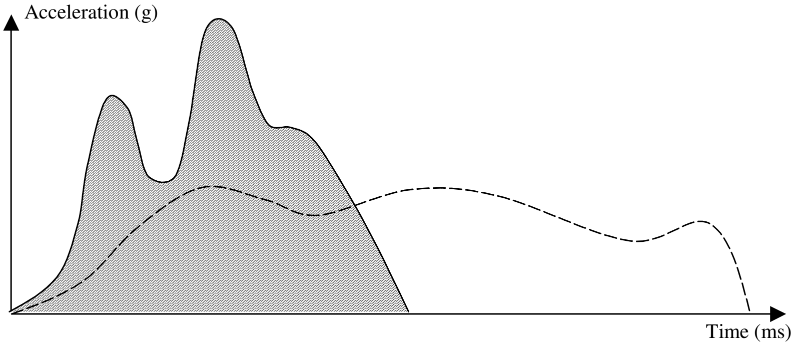

Figure 25. Crash pulse with similar change of velocity and different duration.

6.4.1 Road infrastructure design

In two-vehicle crashes there was a higher average crash severity on rural roads than on urban roads (Study I). Conclusions from studies of speed correlated to injury risk such as Finch et al.(1994) support the belief that lower speed has strong positive implications for crash severity, regardless of type of road infrastructure. Because results such as those reported by Kloeden et al. (1997) show a faster increase in serious injury crash rate with a particular increase in speed on minor/urban roads than on major/rural roads, differences in crash severity between urban and rural areas need to be further investigated. In future research, it is necessary to identify how crash severity correlates with driving speed and understand how other factors such as land use, friction, crash type and objects and active vehicle safety systems influence this correlation.

6.4.2 Road-related issues - Deformable and rigid guardrails

Collision partners in single crashes are either man-made objects such as poles and guardrails or natural objects such as trees and embankments. In safety research, objects are often divided into deformable and rigid objects. Guardrails, from flexible wire rope guardrails to rigid concrete-guardrails, are increasingly used in both hazardous roadside areas and as mid guardrails. Study II shows that crash severity (change of velocity and mean acceleration) is more than 40% higher in crashes into rigid objects than into deformable objects. Rigid guardrails generate approximately 40% higher crash severity than deformable guardrails (study II), which is supported from results in study IV showing large differences in crash severity depending on guardrail type.

Rebound speed after hitting a guardrail affects the risk of sustaining an injury in a possible second impact. Study IV shows that a rigid guardrail has the largest rebound exit speed. Flexible guardrails tend to cause less rebound than rigid guardrails. According to Naing et al. (2008), fatalities due to rebounding into the road after impact are more prevalent than in the sample of contained impacts. This means that rigid guardrails should be used less unless deflection is not acceptable (Thomson et al., 1999).

Figure 26 shows crash severity from real-world single crashes (n = 37) into guardrails without any second impact. Crash test data are also plotted from study IV

(110 km/h 20º and 80 km/h 45º). The crash severity is measured in the x-direction. The two lines represent an approximate 10% MAIS2+ injury risk level from study III (22 km/h and 6g). Of the 37 cases from real-world cases, only one had an MAIS2+ injury. The real-world cases show that guardrails generally create low acceleration and are a good solution to avoid more hazardous objects or when used as mid guardrails. Five cases with a change of velocity of up to 39 km/h had minor or no injuries, probably due to moderate levels of acceleration. The property of a guardrail assumes that the vehicle does not overrun the rail or cause intrusion. The results from the 45º tests illustrate that there is a risk of intrusion if the approach angle is large in combination with a stiff guardrail. As the test shows, the amount of intrusion can be extensive although the mean acceleration or change of velocity is moderate.

The crash tests show the large difference in acceleration and change of velocity for various guardrails and large test angle compared to the small differences for the 20º test angle. The results from this thesis suggest that acceleration should be used as the dimensional factor and the interaction between guardrail design and vehicle design should assure that intrusion is minimized.

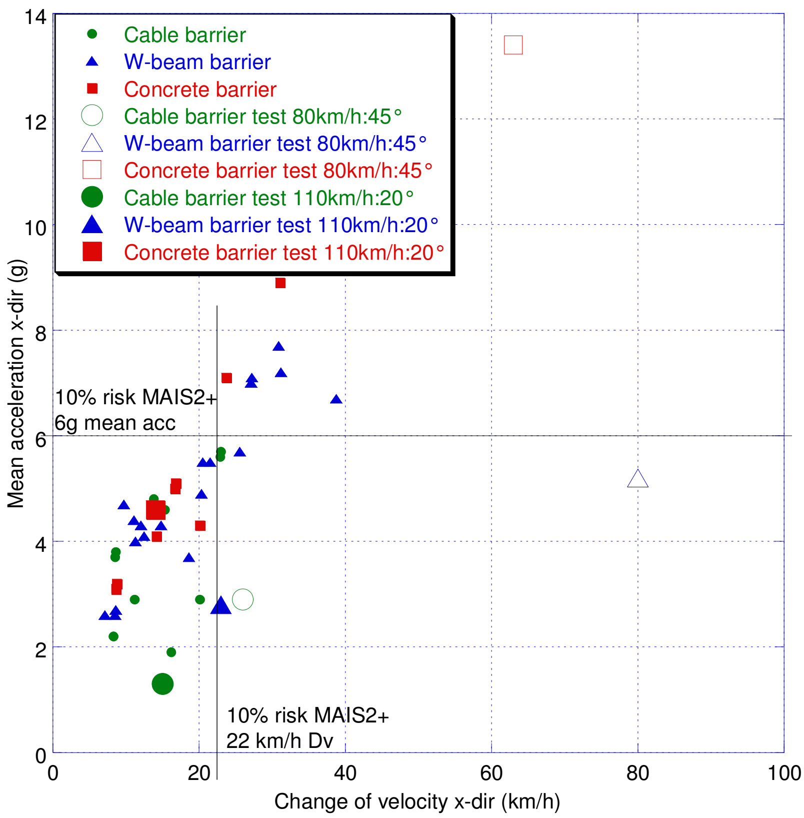

Figure 26. Real-world guardrail crash impacts (n = 37) and guardrail tests (n = 6) from Study IV.

6.4.2.1 Two-vehicle crashes - vehicle sizes

Study II shows that the highest crash severity was generated in two-vehicle frontal crashes. The difference in change of velocity depending on the car collision partner (personal vehicle except MPV, SUV, Bus and HGV) was less than 2 km/h (16.7 km/h to 18.4 km/h) and not significant. One reason for a relatively small difference is that these cars with measured crash severity had an impact direction between ±30° while the collision partners could have any impact direction. This makes the difference in crash severity depend less on size of vehicle when compared with oncoming two-vehicle crashes. Study I clearly shows that an oncoming vehicle crash is the most severe two-vehicle crash type in real-world crashes. Although the mean crash severity in car crashes into HGV vehicles are relatively low, the distribution of individual crash severity is large which also is concluded by Evans (1994b). Evans (1994b) stated that a driver in a vehicle with half the curb weight compared to the opposite vehicle is 12 times more likely to sustain a fatal injury in an oncoming crash. This is so far not verified theoretically and should be further analyzed in future research.

6.5 FINAL COMMENTS

From real-world crashes, this thesis has shown important results about crash severity and injury risk that will help find acceptable crash severity levels below injury tolerance limits. This thesis has also revealed important crash severity parameters: change of velocity, mean acceleration and peak acceleration. Mean acceleration, with its ability to also consider pulse duration, is the most important one to be used as design guideline of a safe transport system.

In real-world crashes, both vehicle acceleration and intrusion are factors contributing to serious and fatal injuries. To reduce injury risk in frontal crashes, the car structure and interior safety systems must be designed to generate acceptable acceleration and at the same time limit occupant compartment intrusion. The stiffer a car structure is constructed, the larger are the acceleration levels generated in a crash. These two parameters have to be considered. High accelerations in a stiff vehicle can be compensated with the design of interior safety systems such as seat belt technology and airbags. The injury risk curve in study III (Figure 16) shows the connection between injury risk and mean acceleration. For higher levels of mean acceleration the number of crashes with intrusion also increases. The amount of intrusion depends on overlap, structure shape and stiffness of the vehicle and of the opposite part. Results from crash tests with various guardrail designs and vehicle structures (Delannoy et al., 2005) have shown large variations in intrusion level and mean acceleration. Their results show from frontal offset crash tests examples with no intrusion at a mean acceleration of 13 g. A crash test with small overlap by Kullgren et al. (1998) resulted in intrusion for only 4 g mean acceleration. It is therefore important to analyze the correlation between mean acceleration and intrusion. The responsibility of the road designer is not only to keep the mean acceleration or other deciding severity parameters below critical levels. The responsibility should also contain guidelines for avoiding objects that cause vehicle compartment intrusion.

Except from guardrail standards, road designers often use best practice measures (EC, 2003). The car industry has more or less to adopt their crashworthiness to existing roads. It is therefore important to understand under what condition the severity of crashes take place. The findings in this thesis can influence the design of the roadside environment for improved crashworthiness as well as for improvement of the safety design of vehicles.

This study shows good correlation of change of velocity to injury but not that useful as a road design guideline. Since the results from this thesis shows large variations in duration, the most meaningful crash severity parameter would therefore be mean acceleration. Acceleration has so far not been used to any great extent in injury risk calculations. How acceleration measured in real-world collisions influences injury risk is an important step in forming a strategy where a large change of velocity could be tolerated as long as the acceleration is kept low.

One crucial question is up to what level in crash severity vehicles are able to protect their occupants. Important is also to cover all injury severity levels. AIS1 injuries, especially AIS1 neck injuries, account for approximately 70% of injuries leading to permanent medical impairment (Malm et al., 2008). One fourth of all AIS1 neck injuries occur in frontal impacts (Krafft, 1998; Berglund, 2002; Krafft et al., 2002). AIS1 neck injuries in both rear end and frontal impacts should preferably be handled by interior safety systems in the car, since they mostly occur in low speed impacts (Kullgren et al., 2000a). But MAIS3+ injuries are the most commonly used injury severity addressing fatal and serious injuries. The literature and car models of today indicate that efficient driver protection regarding MAIS3+ injuries in impact speeds up to 80 km/h is possible (Pipkorn et al., 2005). Another crucial question concerns the maximum tolerated injury risk that need to be decided in the design of a safe transport system. An example of this is presented in EuroNCAP test protocol (EuroNCAP, 2009). EuroNCAP uses 64 km/h as the test speed in frontal crash tests. The choice of speed is based on two performance limits used in frontal impact assessment. The high performance limit corresponds to a 5% risk of AIS3+ injury and the low performance limit corresponds to a 20% risk of AIS3+ injury. If these injury risk performance limits were applied to injury risk presented in study III, the limits of mean acceleration would be:

Low performance limit: approximately 13g mean acceleration
High performance limit: approximately 8g mean acceleration

7 CONCLUSIONS

1. Crash severity is not only dependent on the crash object itself, but also on the road environment in which the crash occurs. The study shows a larger change of velocity on roads with a posted speed limit of 90 km/h than those with a limit of 70km/h. The most severe crashes by land use were two-vehicle crashes in rural areas of which collisions with oncoming vehicles were the most severe crash type. Dry roads were shown to create larger changes of velocity and mean acceleration than did snowy and icy roads in single-vehicle crashes.
2. A long duration of the crash pulse does not lead to high injury risk as long as the mean and peak accelerations are low.
3. In the design of cars and roadside objects, the main design criteria should be acceleration as the findings suggest that long duration can be handled.
4. Crash severity was found to differ depending on collision partner. Frontal two-vehicle crashes and single-vehicle crashes with rigid objects were shown to generate the highest crash severity.
5. There was a lower crash severity in single-vehicle crashes with deformable objects than with rigid objects.
6. A higher proportion of frontal two-car crashes where the change of velocity exceeded 45 km/h occurred in collisions with HGVs than in collisions with small cars (22% compared to 2%).
7. To achieve moderate crash severity, a certain deflection of the guardrail is necessary even for rather small impact angles.
8. Deformable guardrails such as wire rope and w-beam have a large potential to reduce injuries in several situations and are useful for a wide range of impact angles.
9. The concrete guardrail can be used in areas where no deflection can be accepted and where the combination of expected angles and travel speed will not create a situation where the injury risk is too high.

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9 REFERENCES

AAAM. (2005) Abbreviated Injury Scale Association for the Advancement of Automotove Medicine. Barrington, IL, USA.

Aga M. and Okada A. (2003) Analysis of vehicle stability control (VSC)'s Effectiveness from Accident Data. *18th International Technical Conference on the Enhanced Safety of Vehicles*, pp.19-22.

Alsop J. and Langley J. (2001) Under-reporting of motor vehicle traffic crash victims in New Zealand. *Accid. Anal. Prev.* 33(3): pp.353-359.

Amoros E., Martin J.-L. and Laumon B. (2006) Under-reporting of road crash casualties in France. *Accid. Anal. Prev.* 38(4): pp.627-635.

Aptel I., Salmi L.R., Masson F., Bourdé A., Henrion G. and Erny P. (1999) Road accident statistics: discrepancies between police and hospital data in a French island. *Accid. Anal. Prev.* 31(1-2): pp.101-108.

ATC. (2008) National Road Safety Action Plan 2009 and 2010. Australian Transport Council, Canberra, Australia.

Augenstein J.S., Perdeck E.B., Mostafa K.I., Digges K.H., Bahouth G.T. and Morgan R.M. (2005) The role of intrusion in injury causation in frontal crashes. SAE 2005 World Congress & Exhibition,

Bahouth G.T. (2005) Real World Crash Evaluation of Vehicle Stability Control (VSC) Technology. *Association for the Advancement of Automotive Medicine*, pp.19-34.

Bédard M., Guyatt G.H., Stones M.J. and Hirdes J.P. (2002) The independent contribution of driver, crash, and vehicle characteristics to driver fatalities. *Accid. Anal. Prev.* 34(6): pp.717-727.

Berg A., Walz F., Muser M., Bürkle H. and Epple J. (1998) Implications of velocity change delta-v and energy equivalent speed EES for injury mechanism assessment in various collision configurations. *International Research Council on the Biomechanics of Impact (IRCOBI)*, pp.57-72.

Berglund A. (2002) On associations between different factors and whiplash injury:Epidemiological studies on risk of initial and future complains. Doctor in Medical Science Thesis, Karolinska Institutet, Stockholm.

Buzeman D.G., Viano D.C. and Lovsund P. (1998) Injury probability and risk in frontal crashes: effects of sorting techniques on priorities for offset testing. *Accid. Anal. Prev.* 30(5): pp.583-595.

European Committee for Standardization (CEN), (1998a), Road restraint systems - Part 1: Terminology and general criteria for test methods European Standard EN 1317-1

European Committee for Standardization (CEN), (1998b), Road Restraint Systems - Part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers

European Standard EN 1317-2

Coelingh E., Jacobsson L., Lind H. and Lindman M. (2007) Collision warning with auto brake - a real-life safety perspective. *20th International Technical Conference on the Enhanced Safety of Vehicles*, pp.1-9.

Corben B., Hamish D., Mullan N. and Dyte D. (1997) The general effectiveness of countermeasures for crashes into fixed roadside objects. Monash University Accident Research centre, Melbourne.

Dang J.N. (2004) Preliminary results analyzing the effectiveness of Electronic stability Control (ESC) systems. NHTSA, Washington.

de Leur P., Abdelwahab W. and Navin F. (1994) Evaluating hazardous roadsides using computer simulation. *Journal of Transportation Engineers* 120(2): pp.229-245.

Delaney A., Langford J., Corben B.F., Newstead S.V. and Jacques N. (2002) Roadside environment safety. Monash University Accident Research Centre, Melbourne, Australia.

Delannoy P., Martin T. and Castaing P. (2005) Comparative Evaluation of Frontal Offset Tests to Control Self and Partner Protection, pp.1-12.

E. Commission, (2001), White Paper - European transport policy for 2010: Time to decide, Office for Official Publications of the European Communities, ISBN 0-442-00163-0, Luxembourg, Netherlands

E. Commission, (2003), Road infrastructure safety management, European Commission, Brussels, Belgium

Elvik R. (1995) The safety value of guardrails and crash cushions: A meta-analysis of evidence from evaluation studies. *Accid. Anal. Prev.* 27(4): pp.523-549.

ETSC. (1998) Forgiving roadsides. E. T. S. Council, Brussels.

ETSC. (2001) Sharing responsibilities for road safety. E. T. S. Council, Brussels.

EuroNCAP. (2009) Assessment protocol - adult occupant protection.

Evans L. (1994a) Car size and safety. *14th International Technical Conference on the Enhanced Safety of Vehicles*.

Evans L. (1994b) Driver injury and fatality risk in two-car crashes versus mass ratio inferred using Newtonian mechanics. *Accid. Anal. Prev.* 26(5): pp.609-616.

Faerber E. (2005) EEVC Approach to the Improvement of Crash Compatibility between Passenger Cars. 19th International Technical Conference on the Enhanced Safety of Vehicles, pp.1-5.

Farmer C.M. (2001) New evidence concerning fatal crashes of passenger vehicles before and after adding antilock braking systems. *Accid. Anal. Prev.* 33(3): pp.361-369.

Farmer C.M. (2004) Effect of Electronic Stability Control on Automobile Crash Risk. *Traffic Injury Prevention* 5(4): pp.317 - 325.

Ferguson S.A. (2007) The Effectiveness of Electronic Stability Control in Reducing Real-World Crashes: A Literature Review. *Traffic Injury Prevention* 8(4): pp.329 - 338.

Finch D.J., Kompfner P., Lockwood C.R. and Maycock G. (1994) Speed, speed limits and crashes. TRL, Transport Research Laboratory, Berks, UK.

Fincham W.F., Kast A. and Lambourn R.F. (1995) The use of a high resolution accident data recorder in the field. SAE 1995 World congress & Exhibition,

Funk J.R., Cormier J.M. and Gabler H.C. (2008) Effect of Delta-V Errors in NASS on Frontal Crash Risk Calculations. *Association for the Advancement of Automotive Medicine*, pp.155-164.

Gabauer D.J. and Gabler H.C. (2008a) Accelerationbased occupant injury criteria for predicting injury in realworld crashes. *Biomed. Sci. Instrum.* 44: pp.213-218.

Gabauer D.J. and Gabler H.C. (2008b) Comparison of roadside crash injury metrics using event data recorders. *Accid. Anal. Prev.* 40(2): pp.548-558.

Gabler H.C., Hampton C. and Roston T.A. (2003) Estimating crash severity:can event data recorders replace crash reconstruction? *18th International Technical Conference on the Enhanced Safety of Vehicles*, pp.1-12.

Gabler H.C., Hampton C.E. and Clayton L.T. (2004) Crash Severity:A comparison of Event Data Recorder Measurements with Accident Reconstruction Estimates. SAE 2004 World Congress & Exhibition, pp.1-8.

Gadd W. (1966) Use of a Weighted Impulse Criterion for Estimating Injury Hazard. *STAPP Car Crash Conference*, pp.164-174.

Garber S. and Graham J. (1990) The effects of the new 65 mile per hour speed limit on rural highway fatalities: A state-by-state analysis. *Accid. Anal. Prev.* 22(2): pp.137-149.

Geigl B.C., Hoschopf H., Steffan H. and Moser A. (2003) Reconstruction of occupant kinematics and kinetics for real world accidents. *International Journal of Crashworthiness* 8(1): pp.17 - 27.

Giess M. and Tomas J. (1998) Improving safety performance in frontal collisions by changing the shape of structural components. *16th International Technical Conference on the Enhanced Safety of Vehicles*, pp.1-7.

Glaister D.H. (1978) Human tolerance to impact acceleration. *Injury* 9(3): pp.191-198.

Guo H., Eskridge K.M., Christensen D., Qu M. and Safranek T. (2007) Statistical adjustment for misclassification of seat belt and alcohol use in the analysis of motor vehicle accident data. *Accid. Anal. Prev.* 39(1): pp.117-124.

Harwood D.W., Bauer K.M., Potts I.B., Torbic D.J., Richard K.R., Rabbani E.R.K., Hauer E., Elefteriadou L. and Griffith M. (2003) Safety effectiveness of

intersection left- and right-turn lanes *Journal of the Transportation Research Board* 1840: pp.131-139.
Huang M. (2002) Vehicle crash mechanics. Dearborn, Michigan, US, CRC press.
Hudson C.L. (1972) Development of a vehicle mounted crash recorder. National Highway Traffic Safety Administration, Washington D.C., USA.
Håland Y., Lovsund P. and Nygren A. (1993) Life-threatening and disabling injuries in car-to-car side impacts--implications for development of protective systems. *Accid. Anal. Prev.* 25(2): pp.199-205.
Håland Y., Lövsund P. and Nygren A. (1990) Estimation of fatalities and disabilities in car to car side impacts:An evaluation of different risk factors. *Association for the Advancement of Automotive Medicine*, pp.275-287.
Hägg A., Krafft M., Kullgren A., Lie A., Malm S., Tingvall C. and Ydenius A. (2001) Folksam Car Model Safety Ratings 2001. F. I. Company, Folksam Insurance Company, Stockholm.
Jenefeldt F. and Thomson R. (2004) A methodology to assess frontal stiffness to improve crash compatibility. *International Journal of Crashworthiness* 9(5): pp.475 - 482.
Joksch H.C. (1993) Velocity change and fatality risk in a crash - a rule of thumb. *Accid. Anal. Prev.* 25(1): pp.103-104.
Kloeden C.N., McLean A.J., Moore V.M. and Ponte G. (1997) Travelling speed and the rate of crash invlovement., FORS, Federal Office of Road Safety, Canberra.
Krafft A. (1998) Non-fatal injuries to car occupants:Injury assessment and analysis of impacts causing short- and long-term consequences with special reference to neck injuries. Doctor in Medical Science Thesis, Karolinska Institute, Stockholm.
Krafft M., Kullgren A., Lie A., Strandroth J. and Tingvall C. (2009) The effects of automatic emergency braking on fatal and serious injuries. *21st International Conference on Enhanced Safety of Vehicles*.
Krafft M., Kullgren A., Ydenius A. and Tingvall C. (2001) The correlation between crash pulse characteristics and duration of symptoms to the neck-crash recording in real life rear impacts. *17th International Technical Conference on the Enhanced Safety of Vehicles*, pp.1-7.
Krafft M., Kullgren A., Ydenius A. and Tingvall C. (2002) Influence of Crash Pulse Characteristics on Whiplash Associated Disorders in Rear Impacts--Crash Recording in Real Life Crashes. *Traffic Injury Prevention* 3(2): pp.141 - 149.
Krusper A. and Thomson R. (2008) Crash compatibility between heavy goods vehicles and passenger cars: structural interaction analysis and in-depth accident analysis. *International Conference on Heavy Vehicles*.
Kullgren A. (1998) Validity and Reliability of Vehicle Collision Data:Crash Pulse Recorders for Impact Severity and Injury Risk Assessments in Real-Life Frontal Collisions. Doctor in Medical Science Thesis, Karolinska Institute, Stockholm.
Kullgren A. (2008) Dose-Response Models and EDR Data for Assessment of Injury Risk and Effectiveness of Safety Systems. *International Conference on the Biomechanics of Impact (IRCOBI)*, pp.3-14.
Kullgren A., Krafft M., Malm S., Ydenius A. and Tingvall C. (2000a) Influence of airbags and seatbelt pretensioners on AIS1 neck injuries for belted occupants in frontal impacts. *STAPP Car Crash Coference*, pp.1-9.
Kullgren A., Krafft M., Nygren Å. and Tingvall C. (2000b) Neck injuries in frontal impacts: influence of crash pulse characteristics on injury risk. *Accid. Anal. Prev.* 32(2): pp.197-205.
Kullgren A., Krafft M., Ydenius A., Lie A. and Tingvall C. (2002) Developments in car safety with respect to disability-Injury distributions for occupants in cars from the 80s and 90s. *International Research Council on the Biomechanics of Impact (IRCOBI)*, pp.145-154.
Kullgren A., Lie A. and Tingvall C. (1994) The effectiveness of ABS in real life accidents. 14th International Technical Conference on the Enhanced Safety of Vehicles,
Kullgren A., Lie A. and Tingvall C. (1995) Crash pulse recorder--validation in full scale crash tests. *Accid. Anal. Prev.* 27(5): pp.717-727.

Kullgren A., Ydenius A. and Tingvall C. (1998) Frontal impacts with small partial overlap: real life data from crash recorders. *International Journal of Crashworthiness* 3(4): pp.335 - 346.
Larsson J. (2006) Olyckstyper-klassificering. Swedish National Road and Transport Research Institute, Linköping, Sweden.
Lenard J., Hurley B. and Thomas P. (1998) The accuracy of CRASH3 for calculating collision severity in modern European cars. *16th International Technical Conference on the Enhanced Safety of Vehicles*, pp.1-8.
Lie A., Tingvall C., Krafft M. and Kullgren A. (2004) The Effectiveness of ESP (Electronic Stability Program) in Reducing Real Life Accidents. *Traffic Injury Prevention* 5(1): pp.37 - 41.
Lindquist M., Hall A. and Björnstig U. (2004) Car structural characteristics of fatal frontal crashes in Sweden. *International Journal of Crashworthiness* 9(6): pp.587 - 597.
Linnskog P. (2007) Safe Road Traffic-Systematic quality assurance based on a model for safe road traffic and data from in-depth investigations of traffic accidents. *EuroRAP AISBL 5th General Assembly Members' Plenary Session*, pp.1-20.
Lum H. and Reagan J.A. (1995) Interactive highway safety design model.
Lynam D., Sutch T., Broughton J. and Lawson S.D. (2003) European road assessment program pilot phase. Farnborough, UK.
Malm S., Krafft M., Kullgren A., Ydenius A. and Tingvall C. (2008) Risk of permanent medical impairment (RPMI) in road traffic accidents. *Annu Proc Assoc Adv Automot Med* 52: pp.93-100.
Mills F.J. and Harding R.M. (1983) Acceleration. II: short duration acceleration. *Br. Med. J.* 286(6378): pp.1630-1631.
Morris A., Ruth W., Jo B. and Richard F. (2006) The nature, type and consequences of lower extremity injuries in front and side impacts in pre and post regulatory passenger cars. *International Research Council on the Biomechanics of Impact (IRCOBI)*, pp.19-34.
Naing C.L., Hill J., Thomson R., Fagerlind H., Kelkka M., Klootwijk C., Dupre G. and Bisson O. (2008) Single-vehicle collisions in Europe: analysis using real-world and crash-test data. *International Journal of Crashworthiness* 13(2): pp.219 - 229.
Neptune J.A. (1999) A comparison of crush stiffness characteristics from partial-overlap and full-overlap frontal crash tests. International Congress and Exposition,
Niehoff P. and Gabler H.C. (2006) The accuracy of WinSmash delta-V estimates: the influence of vehicle type, stiffness, and impact mode. *Annu Proc Assoc Adv Automot Med* 50: pp.73-89.
Niehoff P., Gabler H.C., Brophy J., Chidester C., Hinch J. and Ragland C. (2005) Evaluation of event data recorders in full systems crash tests. *19th International Technical Conference on the Enhanced Safety of Vehicles*, pp.1-16.
Nilsson G. (1982) The effects of speed limits on traffic crashes in Sweden. *International symposium on the effects of speed limits on traffic crashes and fuel consumption*, pp.1-10.
Nilsson G. (2004) Traffic safety dimensions and the power model to describe the effect of speed on safety. Doctor's Thesis, Lunds Institute of Technology, Lund.
Norin H. (1995) Evaluating the crash safety level components in cars. Doctor in Philosophy Thesis, Karolinska Institutet, Stockholm.
Norin H. and Isaksson-Hellman I. (1995) Injury potential prediction of a safety design feature: A theoretical method based on simulations and traffic accident data. *Safety Science* 19(1): pp.44-56.
Norin H., Krafft M., Korner J., Nygren A. and Tingvall C. (1997) Injury severity assessment for car occupants in frontal impacts, using disability scaling. *J. Clin. Epidemiol.* 50(1): pp.95-103.
OECD. (1998) Definitions and data availability:compilation and evaluation of A-level roads and hospitalised victims in OECD countries. O. R. T. R. Programme, Germany.
OECD. (2002) Safety on roads: What´s the vision? Organization for economic co-operation and development Paris.

Park C.-K., Thomson R., Krusper A. and Kan C.-D. (2009) The Influence of Sub-Frame Geometry on a Vehicle's Frontal Crash Response. *21st International Conference on Enhanced Safety of Vehicles*

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

Pipkorn B. (2009) Effects of active structures on injuries in medium severity frontal impacts. *21st International Conference on Enhanced Safety of Vehicles*, pp.1-8.

Pipkorn B., Mellander H. and Haland Y. (2005) Car driver protection at frontal impacts up to 80km/h. *19th International Technical Conference on the Enhanced Safety of Vehicles*, pp.1-8.

Ramos G., Perandones J.M., Alonso M., Plaza J. and Henar V. (2008) Final report TREN-04-FP6TR-S07.36996/001678. RANKERS, Ranking for European Road Safety,

Rasmussen J. (1997) Risk management in a dynamic society: a modelling problem. *Safety Science* 27(2): pp.183-213.

Renski H., Khattak A.J. and Council F.M. (1999) Impact of speed limit increases on crash injury:Analysis of single-vehicle crashes on North Carolina Interstate highways. *Transportation research record*, pp.100-108.

RISER. (2003) Road infrastructure for safer European roads - D05 Summary of European design guidelines for roadside infrastructure. Chalmers University of Technology, Gothenburg, Sweden.

Rizzi M., Strandroth J. and Tingvall C. (2009) The Effectiveness of Antilock Brake Systems on Motorcycles in Reducing Real-Life Crashes and Injuries. *Traffic Injury Prevention* 10(5): pp.479 - 487.

Ross J.H.E., Sicking D.L., Zimmer R.A. and Michie J.D. (1993) NCHRP Report 350 Recommended procedures for the safety performance evaluation of highway features. Transportation Research Board National Research Council, Washington D.C.

Ross R., Lenard J., Hurley B., Thomas P., Otte D. and Vallet G. (1998) Crash severity calculations - Theory and Practice., STAIRS, Standardisation of accident and injury registration systems,

Sabey B.E. and Taylor H. (1980) The known risks we run: the highway., Transport and Road Research Laboratory, Crowthorne, Berks.

Salomonsson O. and Koch M. (1991) Crash recorder for safety system studies and as a consumers product. SAE 1991 World congress & Exhibition,

Schiff M.A. and Cummings P. (2004) Comparison of reporting of seat belt use by police and crash investigators: variation in agreement by injury severity. *Accid. Anal. Prev.* 36(6): pp.961-965.

Schram R., Leneman F.J.W., van der Zweep C.D., Wismans J.S.H.M. and Witteman W.J. (2006) Assessment criteria for assessing energy-absorbing front underrun protection on trucks. *International Journal of Crashworthiness* 11(6): pp.597 - 604.

Sherwin J.R. and Kerr J.D. (1979) Advanced Recorder Design Development., National Highway Traffic Safety Administration, Washington, DC.,USA.

SIKA. (2004) Communications No 1 2004. Swedish institute for transport and communications analysis statistics in Sweden, Stockholm.

SIKA. (2007) Road Traffic Injuries 2006. Swedish institute for transport and communications analysis statistics in Sweden, Östersund, Sweden.

SIS. (2002). Road Vehicles - Traffic Accident Analysis Part 1:Vocabulary, International Organization for Standardization ISO.

SIS. (2003). Road vehicles- Traffic accident analysis. Part 2: Guidelines for the use of impact severity measures, International Organization for Standardization ISO.

SRA. (2005) Halkolyckor med dödlig utgång - Analys av Vägverkets djupstudiematerial 2000-2004. Swedish Road Administration, Borlänge, Sweden.

Stigson H. (2009a) Evaluation of Safety Ratings of Roads Based on Frontal Crashes with Known Crash Pulse and Injury Outcome. *Traffic Injury Prevention* 10(3): pp.273 - 278.

Stigson H. (2009b) A safe road transport system - Factors influencing injury outcome for car occupants. Doctor's Thesis, Karolinska Institute, Stockholm.
Stigson H. and Hill J. (2009) Use of car crashes resulting in fatal and serious injuries to analyze a safe road transport system model and to identify system weaknesses. *Traffic Inj Prev* 10(5): pp.441-450.
Stigson H., Krafft M. and Tingvall C. (2008) Use of fatal real-life crashes to analyze a safe road transport system model, including the road user, the vehicle, and the road. *Traffic Inj Prev* 9(5): pp.463-471.
Strandroth J. (2009) In-depth analysis of accidents with heavy goods vehicles- Effects of measures promoting safe heavy goods traffic. Borlänge, Sweden.
Stucki S.L. and Fessahaie O. (1998) Comparison of Measured Velocity Change in Frontal Crash tests to NASS Computed Velocity Change. *SAE Conference*.
Synergy Software. (2000). KaleidaGraph, Synergy Software.
Sörensen M. (2007) Best Practice Guidelines on Black Spot Management and Safety Analysis of Road Networks. Institute of Transport Economics Norwegian Centre for Transport Research, Oslo, Norway.
Teel S.S., Peirce S.J. and Lutkefedder N.W. (1974) Automotive Recorder Research - Disc Recorder Pilot Project. Volume II: Results of Tests and Evaluations., National Highway Traffic Safety Administration, Washington, DC.;USA.
Thomas P., Charles J. and Fay P. (1995) Lower Limb Injuries--The Effect of Intrusion, Crash Severity and the Pedals on Injury Risk and Injury Type in Frontal Collisions. SAE 1995 World Congress & Exhibition,
Thomson R. (2004) Compatibility between passenger vehicles and road barriers during oblique collisions. *International Journal of Crashworthiness* 9(3): pp.245 - 253.
Thomson R., Fagerlind H., Martinez A.V., Amenguel A., Naing C., Hill J., Hoschkopf H., Dupré G., Bisson O., Kelkka M., Van der Horst R. and Garcia J. (2006) Roadside infrastructure for safer European roads (RISER).
Thomson R., Romilly D. and Navin F. (1999) Two-dimensional modeling of collision dynamics of deflecting concrete barriers. Transportation Research Record, pp.103-109.
Tingvall C. and Lie A. (1996) The implications of the Vision Zero on biomechanical research.". *International Research Council on the Biomechanics of Impact (IRCOBI)*, pp.11-18.
Tingvall C. and Lie A. (2008). The safe system approach. Paris, International transport forum.
Treat J.R., Tumbas N.S., McDonald S.T., Shinar D., Hume R.D., Mayer R.E., Stansifer R.L. and Castellan N.J. (1979) Tri-level Study of the Causes of Traffic Accidents: Executive Summary., NHTSA, Washington DC, USA.
Tsui K.L., So F.L., Sze N.N., Wong S.C. and Leung T.F. (2009) Misclassification of injury severity among road casualties in police reports. *Accid. Anal. Prev.* 41(1): pp.84-89.
Underwood G., Jiang C. and Howarth C.I. (1993) Modelling of safety measure effects and risk compensation. *Accid. Anal. Prev.* 25(3): pp.277-288.
Wegman F. and Aarts L. (2006) Advancing sustainable safety - National Road Safety Outlook for 2005-2020. SWOV Institute for Road Safety Research, Leidschendam, Netherlands.
Wilkie K., Miller C. and Baird R. (1989) The inexpensive crash recorder project. *Canadian multidisciplinary road safety conference*, pp.251-258.
Wood D.P. and Simms C.K. (2002) Car size and injury risk: a model for injury risk in frontal collisions. *Accid. Anal. Prev.* 34(1): pp.93-99.
Wood D.P., Veyrat N., Simms C. and Glynn C. (2007) Limits for survivability in frontal collisions: theory and real-life data combined. *Accid. Anal. Prev.* 39(4): pp.679-687.
Wågström L., Thomson R. and Pipkorn B. (2005) Structural adaptivity in frontal collisions: implications on crash pulse characteristics. *International Journal of Crashworthiness* 10(4): pp.371 - 378.
Ydenius A. (2002) Influence of crash pulse duration on injury risk in frontal impacts based on real life crashes. *International Research Council on the Biomechanics of Impact (IRCOBI)*, pp.155-166.

Ydenius A. and Kullgren A. (2001) Injury risk functions in frontal impacts using recorded crash pulses. *International Research Council on the Biomechanics of Impact (IRCOBI)*, pp.27-38.

Ydenius A., Kullgren A. and Tingvall C. (2001) Development of a crashworthy system: interaction between car structural integrity, restraint systems and guardrails. *17th International Technical Conference on the Enhanced Safety of Vehicles*, pp.1-12.

Zeidler F., Schreier H. and Stadelmann R. (1985) Accident Research and Accident Reconstruction Method. SAE 1985 World Congress & Exhibition,

Öberg G. (1994) Vädrets och väglagets inverkan på personbilshastigheten: Litteratursammanställning och bearbetning av tidigare genomförda svenska mätningar. VTI, Swedish National Road and Transport Research Institute, Linköping.