Characteristics of nearside car crashes – an integrated approach to side impact safety

Cecilia Sunnevång
To my father
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Abstract

**Introduction:** Approximately 1.25 million people globally are killed in traffic accidents yearly. To achieve the UN Global Goal of a 50% reduction of fatal and serious injuries in 2020 a safer infrastructure, as well as new safety technologies, will be needed. Side crashes represent 20% of all serious and 25% of fatal injuries. The overall aim of this thesis is to provide guidelines for improved side impact protection. First, by characterizing nearside crashes and injury outcome, including injuries from the farside occupant, for non-senior and senior front seat occupants. Second, to determine whether the WorldSID dummy provides opportunities for improved in-crash occupant protection. And third, by relating in-crash occupant protection to pre-crash countermeasures, to explore a holistic approach for side crashes using the integrated safety chain from safe driving to crash.

**Methods:** NASS/CDS data for both older and modern vehicles was used to provide exposure, incidence, and risk for fatal injury as well as detailed injury distribution and crash characteristics. The WorldSID dummy was compared to Post Mortem Human Subjects (PMHS) in impactor tests at high and low severities to demonstrate the possibilities of this tool. Crash tests were performed to evaluate WorldSID crash test dummy assessments of injuries found in the NASS/CDS data. The integrated safety chain was used to demonstrate how to evaluate occupant protection in side crashes from a larger perspective, involving infrastructure and Automated Emergency Braking.

**Result:** Most side crashes occur at intersections. The head, thorax, and pelvis are the most frequently injured body regions, and seniors have a higher risk for rib fractures compared to non-seniors. The WorldSID dummy response was similar to the PMHS response at the higher impact speed, but not at the lower. In conjunction with improved airbags infrastructural change, and the use of Automated Emergency Braking, can effectively reduce the number of fatalities and injured occupants in side impacts.

**Conclusion:** Future focus for side impact protection should be on intersection crashes, improved occupant protection for senior occupants, and protection for and from the farside occupant, reducing injury risk to the head, thorax, and pelvis. The WorldSID dummy has the ability to reproduce humanlike responses in lateral and oblique impacts. However, at a low crash severity, chest deflection could be underestimated, which must be taken into consideration when evaluating, for example, pre-crash inflated side airbags. Analyzing nearside crashes using the integrated safety chain shows that speed management by means of roundabouts is an efficient countermeasure.
reducing the number of injurious crashes, as well as reducing variations in crash severity. In combination with an Automated Emergency Braking a large part of side crashes could be avoided or crash severity mitigated. Rather than developing structures and airbags for high-speed crashes, it is important to consider alternative countermeasures. Hence the need for an integrated approach to side impacts.
# Abbreviations

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<th>Abbreviation</th>
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<tr>
<td>ABS</td>
<td>Antilock Braking System</td>
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<td>ADAS</td>
<td>Advanced Driver Support Systems</td>
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<td>AEB</td>
<td>Automated Emergency Braking</td>
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<tr>
<td>AEB+</td>
<td>Automated Emergency Braking at higher brake level than currently implemented (1.5g)</td>
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<td>AIS</td>
<td>Abbreviated Injury Scale</td>
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<td>ATD</td>
<td>Anthropomorphic Test Device</td>
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<tr>
<td>Delta-V, DV</td>
<td>Delta Velocity (change of velocity)</td>
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<td>EC</td>
<td>European Commission</td>
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<td>ECE R95</td>
<td>European Commission for Europe, Regulation No. 95 (Protection of occupants in the event of lateral collision)</td>
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<td>ESC</td>
<td>Electronic Stability Control</td>
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<td>Euro NCAP</td>
<td>European New Car Assessment Programme</td>
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<td>Euro RAP</td>
<td>European Road Assessment Programme</td>
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<td>EuroSID2</td>
<td>European Side Impact Dummy (version2)</td>
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<td>FMVSS</td>
<td>Federal Motor Vehicle Safety Standards</td>
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<td>GIDAS</td>
<td>German In-Depth Accident Study</td>
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<td>Global NCAP</td>
<td>Global New Car Assessment Programme</td>
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<td>IIHS</td>
<td>Insurance Institute of Highway Safety</td>
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<tr>
<td>IRC</td>
<td>Injury Risk Curve</td>
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<td>LTV</td>
<td>Light Truck or Van</td>
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<tr>
<td>MAIS3+F</td>
<td>Maximum AIS3 including fatal injuries</td>
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<tr>
<td>MDB</td>
<td>Moving Deformable Barrier</td>
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<tr>
<td>NASS/CDS</td>
<td>National Accident Sampling System / Crash Worthiness Data System</td>
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<td>NHTSA</td>
<td>National Highway and Traffic Safety Administration</td>
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<td>PMHS</td>
<td>Post Mortem Human Subject</td>
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<td>SID2s</td>
<td>Side Impact Dummy 2s</td>
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<tr>
<td>SUV</td>
<td>Sport Utility Vehicle</td>
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<td>THOR</td>
<td>Test device for Human Occupant Restraint</td>
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<td>TTC</td>
<td>Time to collision</td>
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<td>US NCAP</td>
<td>US New Car Assessment Programme</td>
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<td>V2X</td>
<td>Vehicle to vehicle or infrastructure communication</td>
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<td>WorldSID, WSID</td>
<td>Worldwide Side Impact Dummy, 50th percentile male</td>
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List of Publications

This thesis is based on the following five publications, which will be referred to in the text as Studies I-V:

Study I

Study II

Study III

Study IV

Study V
Background

Traffic injuries and fatalities are an increasing global health problem. If current injury rates are sustained, traffic accidents will be the fifth cause of death for the younger population in 2020 (WHO 2015). Currently, approximately 1.25 million people throughout the world die in traffic accidents yearly. Half are occupants of 4-wheeled motor vehicles, while the remainder drive powered two-wheelers, are cyclists, or pedestrians (WHO 2015). In the US in 2009, approximately 2 million motor vehicle occupants were injured, and 22,383 of these were fatally injured. (NHTSA 2013). In Europe (EU25) 10,950 motor vehicle occupants were fatally injured in 2013 (EC 2015a).

In the Decade of Action for Road Safety 2011-2020 safer vehicles are considered one of the key pillars of the Decade Action Plan (UN 2010). The action plan specifically addresses the promotion of safety systems through harmonization of global standards, consumer information, and incentives to accelerate the implementation of new technology (UN 2010). In the 2030 Agenda for Sustainable Development, launched by the UN in September 2015, road safety was included for the first time, and one of the Global Goals was to reduce global road traffic fatalities and injuries by 50% between 2010-2020 (UN 2015).

The road transport safety strategy Vision Zero, aiming toward no fatalities or serious injuries in the road transport system, was adopted by the Swedish government in 1997 (Swedish Government 1997). As in other safety policies Vision Zero is based on Haddon’s principles of focusing not only on one main accident causation factor, but to work with a systematic combination of causation, and the effect of countermeasures (Haddon 1980). The Vision Zero strategy introduced a Safe System Approach, focusing on sharing responsibility between system providers and users in order to reduce injury within the transport system (Tingvall 1995, Tingvall et al. 1996, Tingvall 1997). Since the adoption of Vision Zero in Sweden, focus on countermeasures for safer roads and vehicles, as well as speed management, have decreased road fatalities by approximately 50% (541 in 1997 to 259 in 2015), despite the number of vehicles having increased substantially (Swedish Transport Administration 2016). Other countries and organizations have adopted this approach (Belin 2012), and thereby paved the way for Global Goals.

According to Vision Zero it is important to focus on all aspects of traffic safety (such as driver behavior, infrastructure and vehicles). A safe driver is assumed fit to drive and complying with traffic regulation, which means wearing a
seatbelt, being sober, and complying with speed limits (Stigson 2009). A safe infrastructural design focuses on reducing the number of crashes by, for example, speed management (roundabouts, speed cameras, and road humps), and separated vehicle lanes (Kallberg et al. 1999, VTI 2016). For safer vehicles, Global NCAP has identified prioritized technical solutions that will be promoted through rating schemes (Global NCAP). Technologies in focus are seatbelts (and seatbelt reminders), airbags, tires, Antilock Braking Systems (ABS), Adaptive Cruise Control (ACC), Electronic Stability Control (ESC), and Automated Emergency Brake (AEB) systems.

To evaluate the effects of countermeasures within the Safe System Approach the integrated safety chain was introduced by Tingvall et al. in 2008. The method was further developed by Lie (2012). Strandroth et al. (2012) used the integrated safety chain as a method to demonstrate a combined effect of simultaneous improvements of road and vehicle safety technologies. A more detailed explanation of the integrated safety chain is available in the Method and Materials section, whereby the method is the theoretical framework of this thesis.

Regardless of countermeasure, human injury tolerance and biomechanics constitute the limitations of the road transport system. To investigate the potential for crash avoidance and injury mitigation the dose-response model developed by Kullgren (1998) can be used. Crash severity (exposure) is the input, dose, and injury outcome (incidence), the response. Injury risk function forms the link between input and outcome (Kullgren 2008).

![Figure 1. Dose-response model with methods of reducing the number of injured occupants by moving the curves (1-3) (Kullgren 2008).](image)

By introducing countermeasures that reduce crash severity (1), or the number of crashes (2), or the injury risk (3) the number of injured occupants is reduced. The dose-response model has been applied to real-life data in several

**Side Crashes**

For crashes resulting in serious (AIS3+) and fatal injuries, side crashes are the second most common crash direction (principal direction of force 2-4 and 8-10 o’clock) after frontal crashes (Traffic Safety Facts 2013). Using US national statistics and comparing the ratio of fatal side and frontal crashes, the trend is increasing, implying that the number of frontal crashes with fatal outcomes is being reduced faster than fatal side crashes (Subit et al. 2010). Side crashes account for approximately 20% of all crashes resulting in serious injury, and approximately 25% of all fatalities (Traffic Safety Facts 2013). In the US, approximately 5000 people are fatally injured in side crashes (excluding rollovers). Previous research has shown that occupants exposed to a nearside (seated adjacent to the intruding structure) or farside (seated opposite the intruding structure) crashes have similar exposures, and, regardless of injury outcome, 50% of occupants are seated nearside, and 50% are seated on the farside (Gabler et al. 2005, Fildes et al. 2005, Sander and Boström 2010, Brumbelow et al. 2015). When considering occupants sustaining serious injuries in side crashes the ratio is 65% nearside, and 35% farside, and for fatally injured occupants, 75% nearside, and 25% farside.

For nearside occupants previous studies have shown that the most frequent severely and fatally injured body regions are the head and thorax (Thomas and Frampton 1988, Häland et al. 1993, Yoganandan et al. 2007). Thoracic injuries are more frequent than head injuries in an older age group (Kent et al. 2005a, Augenstein et al. 2005). Including moderate (AIS2+) injuries shows that, after the head and chest, lower and upper extremity injuries are also frequent (Welsh et al. 2007, Yoganandan et al. 2007). Low severity injuries resulting in long-term consequences are injuries to the spine, head and lower extremities (Stigson et al. 2015). For the far side occupant the most frequent serious and fatal injuries were also to the head and thorax, followed by upper and lower extremities (Gabler et al. 2005, Yoganandan et al 2014). For farside occupants low severity injuries to the head, face and lower extremities result in long-term consequences (Stigson et al. 2015).

For side crashes in the US, the most common crash mode is a car-to-car impact (85%), but when serious or fatal injury is considered, a larger portion of the striking vehicles are light trucks or vans (LTV). Due to the difference in front end structure the fatality rate is 2.5 times higher than for being impacted by another car (Prasad et al. 2015). In Europe, the most common side impact crash mode is car-to-car impact (EU 2015a). In side crashes resulting in AIS3+
or fatal injury the maximum residual intrusions are found predominantly at the center of the vehicle’s side or in front of the b-pillar, with a principal direction of force at 9-10 and 2-3 o’clock (Xinghua et al. 2012, Brumbelow et al. 2015). Based on accident data (UK and US) side crashes resulting in serious and fatal injury occur at severities above what is currently (2016) evaluated in consumer rating test procedures (Thomas and Frampton 1999, Brumbelow et al. 2015).

Nearside occupant protection in side crashes is a challenge due to the speed of the event and the short distance between the nearside occupant and the intruding structure. Loading of the occupant, and thereby the injury risk, depends on the speed of the intruding structure, as well as the relative change of velocity, delta-v (Tingvall et al. 2003). The impact speed of the bullet vehicle deforms the target vehicle’s side (intrusion), as well as translating the target vehicle in the impact direction (delta-v). The allotment of intrusion, intrusion speed, and delta-v are dependent on the vehicle mass ratio, the bullet front, and target side structure. To improve occupant protection in side crashes it is therefore important to focus on energy control (Tingvall et al. 2003). This can be done by speed limit restriction (to control impact speed) and control of structural compatibility throughout the vehicle fleet.

**Infrastructural Improvements**

The infrastructural design is an important part of the Safe System Approach. Safe infrastructural design anticipates human errors, and potential impact energy can be controlled (Stigson 2009). When vehicle trajectories cross, crash risk increases. Intersections lead to complex situations, with a high frequency of crashes leading to fatal and serious injuries, as well as property damage. In 2013, 20% of all European fatalities, and 26% of US fatalities occurred at intersections (EC 2015b, NHTSA 2014).

The European Road Assessment Programme (Euro RAP) is a program that, like Euro NCAP for vehicle safety, evaluates and provides star ratings for European road standards with respect to safety. A four-star Euro RAP rating on intersections limits speed to less than 50 km/h (no roundabout), or above 50 km/h requiring grade separation or a roundabout (Stigson 2009).

The most strategic countermeasures for reducing injurious intersection crashes are plane separate intersections, roundabouts, and reduced vehicle speed (Oxley et al. 2004). Roundabouts, an infrastructural design reducing travel speed, can reduce the number of crashes by up to 90%, and reduce serious and fatal injuries by 60-80% (Persaud et al. 2000, Gross et al. 2014).
A roundabout (Figure 2) has fewer points of conflict than a traditional intersection, and specifically addresses crossing path and left turn scenarios.

Figure 2. Roundabout example (NTF 2016).

The effectiveness of conflict reduction of the roundabout compared to signalized intersections was found to be less at intersections exceeding a certain traffic volume, however, for crashes resulting in serious injury, effectiveness was high for all intersections (Gross et al. 2012). Replacing intersections with roundabouts reduces speed, number of conflict points, and number of side crashes, resulting in fewer injuries to car occupants and pedestrians (Persuad et al. 2014, Gross et al. 2012, Hydén and Várhelyi 2000, Retting et al. 2001). However, studies show that car-to-bicycle crashes are increasing in roundabouts as compared to intersections, resulting in more injuries to cyclists (Hydén and Várhelyi 2000, Daniels et al. 2007). The increased risk of injury for cyclists can be due to rules experienced as ambiguous for the right of way between bicycle and car, as well as roundabout design (Hydén and Várhelvi 2000, Sakshaug et al. 2010).

There are several aspects to be considered when designing a roundabout. Diameter, affecting the lateral displacement of the vehicle, will affect speed when approaching the roundabout, and hence traffic flow. Integrating cyclists to the roundabout increases complexity, and the number of conflicts compared to separate cyclist lanes (Daniels et al. 2007, Sakshaug et al. 2010). For older drivers information on an impending roundabout, safe speed while approaching, the number of lanes in the roundabout, and what lane to use when entering and exiting the roundabout, is of primary importance (Lord et al. 2007).

Remaining crash types when replacing a junction with a roundabout are rear-end crashes, entering crashes, crashes to vulnerable road users, and single vehicle crashes to the central island (Mandavilli et al. 2009, Polders et al. 2015). Sideswipes also occur for roundabouts with multiple lanes.
To further reduce side crashes by infrastructural design, separated vehicle lanes have proven effective, even if data sets are small. A benefit analysis, comparing the fatality ratio prior to and after separated lanes, carried out by the Swedish National Road and Transport Institute, showed a 70% reduction of severe and fatal injuries (Vadeby and Björketun 2016).

**Development of Vehicle Safety Systems**

Today, there is a wide range of vehicle safety systems. It is common to divide these systems into active safety systems, often related to the pre-crash phase and used for crash avoidance, and passive safety systems, related to occupant protection during the crash (in-crash) as injury mitigation. This categorization is sometimes confusing. Haddon, for instance, refers to active safety as systems initiated by the driver, and passive as systems initiated by the vehicle (Haddon 1980). A belt system would, in that sense, be considered an active system, which is not presently the case. To best utilize modern technology it is time to avoid categories and refer only to safety systems. As pointed out in the Safe System Approach vehicle safety systems need to be integrated with the road and human user in order to achieve full potential. Consequently, an integrated safety approach is recommended.

During the last few decades, occupant safety, especially for frontal impacts, has been greatly improved (Frampton et al. 2002, Kullgren et al. 2010, Eigen et al. 2012). The structural performance of cars has been upgraded, reducing intrusion into the passenger compartment, and occupant protection systems for injury prevention during the crash phase, have been introduced (Kahane 2004). The seat belt is the most effective in-crash safety system, keeping the occupant in a stable position, and reducing serious and fatal injuries by approximately 40% (Evans 1991, Kahane 2000). Adding the frontal airbag increases the risk-reducing effect in frontal impacts by 60-70% (Kent et al. 2005). However, the seat belt and frontal airbags are less effective (except for preventing ejection) when the vehicle is impacted from the side (Håland 1994, Viano and Paranteau 2010). Since the nearside occupant is exposed to the highest risk of injury, priority for occupant protection has been to reduce loading transferred from the intruding structure to the nearside occupant. The short distance between the occupant and intruding structure, in combination with the rapidity of the event, make side impacts a challenge in terms of occupant protection (Håland 1994).

Epidemiological studies and crash tests concluded that, despite structural improvements, additional occupant protection was needed. Thus, side airbags were developed (Håland 1994, Pipkorn 1996). In 1995 Volvo was the first manufacturer to introduce a thorax protection side airbag, supplied by
Autoliv. In 1998 the inflatable curtain (IC) was introduced as a means of reducing head injuries in side impacts (Öhlund et al. 1998, Bohman et al. 1998).

Legal and rating requirements developed for side impact protection since the mid-90s have resulted in a majority of passenger cars now equipped with airbags, protecting the head and chest for the nearside occupant. Requirements have also contributed to further structural improvements in newer cars, which have reduced intrusion, and reduced the risk of occupant injury (Samaha 2003, Kahane 2007, Welsh et al. 2007, Sunnevång et al. 2010). American accident statistics have shown that airbags protecting the head and thorax reduce the risk of fatal injuries in a side impact by approximately 30% (McCartt and Kyryschenko 2007, Kahane 2014). Using Swedish data Stigson and Kullgren (2011) showed a similar risk reduction for serious injury. However, American and Swedish accident statistics have shown that serious and fatal side impacts occur at higher crash severities than those for which the restraint systems were developed, thus implying that the severity (e.g. impact speeds) in today’s legal and rating tests should be increased (Thomas and Frampton 1999, Arbelaez et al. 2005, SRA 2006, Brumbelow et al. 2015).

As outboard side airbags (protecting nearside occupants from the intruding structure) are becoming standard equipment, attention has also been paid to farside occupants. Of all side impacts, approximately 35% of serious, and 25% of fatal injuries, are sustained by the farside occupant (Gabler et al. 2005, Fildes et al. 2005, Sander and Boström 2010). At high severities side airbags on the struck side also provide protection for the farside occupant (Kahane 2007). However, adding test procedures addressing injuries to farside occupants in moderate severity crashes is recommended to improve overall side impact protection (Boström et al. 2008, Newland et al. 2008).

Studies investigating two front seat occupants exposed to side impacts have found that the nearside occupant injury risk increases by 8% if there is a passenger present, and that in cases with two occupants, the nearside occupant is, to a greater extent, more severely injured than the farside occupant (Newland et al. 2008, Viano and Parentau 2010, Stigson and Kullgren 2011). Injury risk and injury mechanisms for the farside occupant, as well as for the nearside occupant in cars without airbags, are well documented (Thomas and Frampton 1988, Håland et al. 1993 Yoganandan et al. 2007, 2014). However, injuries sustained in airbag-equipped cars, and to the nearside occupant, due to occupant-to-occupant interaction, have not yet been thoroughly investigated.
With improved safety for front seat occupants, attention has also been directed toward the rear seat. Although less frequently occupied than the front seat, rear seat occupants sustain fatal and serious injuries in side crashes. For children, the head, thorax and pelvis are the most frequently injured body regions for restrained occupants (Bohman et al. 2009). In 2008 92% of new cars in the US were equipped with side airbags as standard equipment in the front seat. The corresponding number for the rear seat was 6%. Adding seat-mounted side airbags to the rear seat would substantially reduce occupant injury risk, and also ensure shorter occupants the protection provided by inflatable curtains for taller occupants (Bohman et al. 2009).

In recent years electronic systems have been developed for the improvement of car occupant safety. These can be divided into systems that inform or warn the driver of a critical situation, and systems that intervene to avoid a crash, or mitigate crash severity. Systems, providing situational awareness, vehicle control, and driver monitoring, create new opportunities for crash avoidance and injury mitigation (Schöneburg et al. 2003). These systems are crucial for highly automated driving, where the driver can engage in tasks other than driving (Eugensson et al. 2013).

Two systems that have long been on the market are Anti-lock Braking Systems (ABS) and Electronic Stability Control (ESC). Both are designed to avoid uncontrolled skidding during braking (ABS) and maneuvering (ESC). The ABS prevents tires from locking during hard braking, which enables steering, and ESC was introduced in the late nineties to prevent loss-of-control accidents by helping the driver maintain or regain control of the vehicle when close to losing control. Between the manufacturing years 2000 and 2007 the fitment of ESC into new vehicles increased from 5% to 41%, and by 2017 all new vehicles in the US will be equipped with ESC (Kahane 2012). In Sweden, almost all new cars are fitted with ESC since 2009 (Strandroth 2012). Based on Swedish data the ESC reduces fatal loss of control accidents by 74% (Lie 2012b). This substantial reduction of loss of control accidents could, in terms of side impacts, reduce almost all high severity impacts such as skidding into oncoming traffic, loss of control resulting in impacts to fixed objects, and rollovers.

Newer sensing systems, such as cameras and radar, collecting information on vehicle surroundings, are becoming increasingly implemented. Exterior sensor systems are a must for advanced driver support systems (ADAS) that can warn or intervene in critical situations. One intervention, where exterior sensors are used, is the Automated Emergency Braking, AEB, where the car brakes automatically before an estimated crash. AEB for rear-end crashes has been proven effective using real life data (Isaksson-Hellman and Lindman
2012, Fildes et al. 2015, Chiccihno 2016). A simulation study using left turn intersection crashes included in the German In-Depth Accident Study (GIDAS) showed that AEB activation on the turning vehicle (assuming 100% fleet penetration) reduced the number of crashes by 45% (Sander 2016). If both cars were equipped with AEB 60% of intersection crashes could have been avoided. By braking the bullet vehicle in a side impact when the crash is unavoidable crash severity is reduced, thereby reducing injury risk for the occupant.

Radar and camera systems can also be used to improve the triggering of belt pretensioners and inflatable systems. Belts, airbags, and active structures can be triggered prior to impact if a crash is considered unavoidable (Schöneburg 2015). When the point of no return is passed the vehicle can prepare for the coming crash by firing external airbags on the front of the striking vehicle (Pipkorn et al. 2007) or along the outside of the struck vehicle (Luzon-Narro et al. 2014). External airbags mitigate intrusion, as well as reducing the energy transferred to the occupant. Pre-crash information can also be used to trigger seat mounted side airbags, adjust the armrest, inflate structures in the door to strengthen the structure, or move the seat (Luzon-Narro et al. 2014). Systems as described above have been shown to reduce crash test dummy (SID-IIs and EuroSid2) chest deflection by 20-60% (Pipkorn et al. 2007, Luzon-Narro et al. 2014). It should be noted, however, that a pre-trigger system also has to provide sufficient protection if pre-trigger sensing fails.

**Current Test Protocols for Side Impact**

Since the late 90’s, side impact occupant protection for the front seat driver has met legal requirement and has been evaluated in consumer rating tests such as FMVSS 214 (legal requirement US), ECE-R95 (legal requirement EU), different NCAP procedures, and the Insurance Institute for Highway Safety (IIHS) high moving deformable barrier (MDB) test. Test procedures aim to evaluate occupant protection using available anthropomorphic test devices (ATDs) in scenarios representing characteristics as observed in real life data. Although nearly similar, test procedures (both legal and consumer rating) from different countries vary slightly due to the dummy version used, barrier speed, weight, or rear seat occupant ATD (CARHS 2016). The present thesis will focus on front seat consumer rating tests (US NCAP, Euro NCAP and IIHS), whereby these three large consumer programs are currently inciting the development of side impact occupant protection (Figure 3).

For impacts with narrow objects such as trees and lampposts in a run off road crash, there is a side pole impact test included in Euro and US NCAP. In this test the vehicle is run at 32 km/h into a rigid pole with a diameter of 254 mm
(top of Figure 3). The impact direction is 75 degrees counter clockwise (90 degrees is pure lateral) to add forward motion to the occupant, and the impact point is aligned to the ATD head (Euro NCAP 2015a, NHTSA 2012a).

To represent intersection crashes a moving deformable barrier of different shapes and weights are run into the side of the target vehicle at different impact speeds. To represent a moving target vehicle the US NCAP uses a crabbed barrier that impacts the target vehicle at 27 degrees (NHTSA 2012b). Euro NCAP MDB impacts the target vehicle laterally (Euro NCAP 2012b). The IIHS high barrier is designed as a SUV front, which, due to its height above ground, does not impact the sill of a passenger car, and thereby results in a larger intrusion into the occupant compartment (IIHS 2016).

**Figure 3.** European and US consumer rating test procedures (CARHS 2016).

**Anthropomorphic Test Devices for Side Impact Injury Assessment**

To assess injury risk in a car crash, ATDs, also called crash test dummies, are used as occupants in crash tests. It is important to verify whether the response from the ATDs can represent occupant kinematic behavior, as well as predict injury in representative loading conditions. As safety systems become more refined it is necessary to have a tool sensitive enough to differentiate between systems (including pre-crash triggered airbags), and to represent a wider range of occupants, especially in terms of senior frailty and fragility. The ATDs used in rating procedures are the tools assessing the biomechanical consequences of an occupant involved in a crash.
Dummy measurements correspond to injury criteria representing injuries observed from accident data. To identify injury criteria, and as one way of deriving injury risk curves (IRC) for these criteria, tests using post mortem human subjects (PMHS) can be used. PMHS tests are carried out on specific body regions, or the whole body, in order to identify relevant and reliable injury mechanisms and criteria, corresponding to injuries observed from accident data. By matched dummy tests injury risk curves are created and can be used for occupant risk evaluation.

There are three ATDs used in the aforementioned rating procedures; SID-IIs, ES-2re and WorldSID (Humanetics 2016). The SID-IIs, a 5th percentile small female is used in the front seat in the US NCAP pole test, and in the rear seat barrier test (NHTSA 2012b). It is also used in the front and rear seats in the IIHS high barrier test (IIHS 2016). The small female WorldSID (5th percentile), which is under development, aims for a higher biofidelity rating (measurement of humanlike response) than the current SID-IIs. The ES-2re, and the WorldSID 50th percentile dummies represent the mid-size male (based on American anthropometry data). During the course of work with this thesis the WorldSID 50th was introduced in Euro NCAP (Euro NCAP 2015a, 2015b), and is also proposed for the US NCAP upgrade (NHTSA 2015). Currently, the ES-2re dummy is used in the US NCAP pole and barrier test protocols. (NHTSA 2012).

The ATD biofidelity rating is a measurement of how humanlike the dummy responds compared to PMHS in different test configurations. It is important that the dummy subjected to the same loading as a car occupant, records the overall loading, and can replicate injuries observed in field data. The biofidelity ranking assesses internal kinematic and kinetic responses. Several previous studies have focused on developing corridors wherein the ATD response should be for side impact (ISO 1999, Ruhle 2009). Comparative testing between PMHS, WorldSID 50th percentile, and the ES-2re, shows that the WorldSID exhibits a more biofidelic behavior regarding kinematics and biomechanical responses under lateral load, according to both ISO and NHTSA evaluation schemes (Tylko et al 2005 and 2006, Yoganandan and Pintar 2008, ISO 2008, Ruhle 2009). Comparison of sled tests with and without side airbag also showed an improved biofidelity for WorldSID compared to the EuroSID2 (Kim et al. 2016).

A comparison of crash tests using older and newer cars showed that occupant loading was higher in older vehicles compared to modern (Sunevång et al. 2010). Since side vehicle structures and occupant loading has changed, and side crash occupant protection has been evaluated through consumer rating
tests, there is a need to align real life loading conditions and biofidelity requirements.

Aims

The overall aim of this thesis is to provide guidelines for improved side impact protection. First, by characterizing nearside crashes and injury outcome, including injuries from the farside occupant, for non-senior and senior front seat occupants, and second, by finding out whether the WorldSID dummy provides opportunities for improved in-crash occupant protection based on crash characteristics and injury outcome. Third, by relating in-crash occupant protection to pre-crash countermeasures, to explore a holistic approach for side crashes using the integrated safety chain.

The studies carried out during the development of the thesis focused on occupant in-crash protection. However, with the rapid development of automated driving in conjunction with focus on infrastructural changes for a safer road traffic system, the third aim is necessary to identify prioritized areas for improved side impact protection. Therefore, an additional analysis using the integrated safety chain, including countermeasure effects from other published studies, was performed to reach the overall aim.

Materials and Methods

Different methods were used throughout this thesis, characterized by a holistic approach, based on real life data and laboratory tests. Observing crash outcomes retrospectively for older cars without side airbag protection revealed implications for enhanced side impact protection. To understand the opportunities and potential limitations of the new crash test dummy WorldSID, a back-to-back comparison to the PMHS was performed. To evaluate the nearside occupant injury risk, the WorldSID was tested in a series of crash tests to assess the head and thoracic injury risk when a neighboring occupant was present. As a last step real life data for crashes, including only cars equipped with deploying side airbags, was studied in order to provide guidelines for future protection of occupants in side impact.

In the sections below the theoretical framework for the thesis is described, as well as a more extensive description of the methods used in the studies, and for additional analyses carried out for this thesis.
Theoretical Framework

In the integrated safety chain events from normal driving to a crash were broken down into phases, and in each phase an action/reaction could have occurred, which may have avoided or mitigated the crash somewhere along the chain (Lie 2012). However, there is no clear definition of normal driving. Normal driving usually refers to a common way of driving which can include risky behavior. In the present thesis the integrated safety chain, as shown in Figure 4, starts with safe driving.

![Diagram of the integrated safety chain](image)

*Figure 4. The integrated Safety Chain (Developed from Lie 2012).*

In this thesis safe driving is further developed from the safe driver explained by Stigson (2009). Safe driving is defined as compliance with traffic regulations, meaning that the driver follows traffic regulations (legal BAC, follows speed limits, and adjusts to road and traffic conditions), is attentive, aware of risks, and has proper training, and the cognitive ability to drive. Drivers that deviate from safe driving will enter the next phase, deviation from normal driving. This might arise due to inattention, stress, fatigue, or risky behavior such as speeding. Such deviations can be intervened by infrastructural countermeasures (ex. speed hump) or an onboard safety system (driver alert) in order to return the driver to safe driving as shown in Figure 4 (top arrows). For a remaining portion (Figure 4, horizontal arrows), the situation can escalate to where the vehicle starts to drift, or the gap to the lead vehicle is too small. Again, the driver and vehicle can be brought back to safe driving by a warning or intervention, and if not, a critical situation occurs when a driver loses control of the car, brakes too late, or commits an error leading to an inevitable crash. In the crash the vehicle protection systems should be designed to mitigate occupant loading to below injurious levels.
Focus of the studies included in the present thesis has been on the last phase of the chain; occupant protection in the event of a crash, Figure 5. To provide guidelines for future occupant protection systems the in-crash countermeasures need to be put into a context of future sustainable transport systems in order to understand the impact of a mix of countermeasures throughout the integrated safety chain. Identifying countermeasures and evaluating their effect on crash avoidance and injury mitigation can aid in assigning priorities within road transport safety.

Figure 5. Schematic view of the present thesis and papers.

**Real Life Data Analyses**

To design occupant protection systems, and assess injuries from field data, register studies are often used. In this thesis the American accident database National Accident Sampling System – Crashworthiness Data System (NASS/CDS) has been used for real life data analyses.

NASS/CDS contains in-depth crash studies from 27 primary sampling units throughout the US. For a crash to be investigated, at least one passenger car, light truck or van (LTV), must be so damaged that it must be towed away after the crash. The crash is then investigated with respect to vehicle, occupant, pre-crash, and crash characteristics. Injuries are recorded and registered according to the Abbreviated Injury Scale (AIS) (AAAM 2008). Approximately 5000 crashes are investigated each year. The data can be made nationally representative through a statistically derived system of weighting factors (NHTSA 2015b).

To evaluate differences due to age in real life data, senior occupants were defined as aged 60 or above. The non-senior group included occupants aged 10-59. There is no common definition for entry to the senior stage of life, but increased frailty and fragility are associated with aging (Kent et al. 2009). Previous studies of biomechanical responses have used different cut-off ages, ranging from 40-70 years (Evans 1991, Viano and Ridella 1996, Zhou et al.
Human bone and soft tissue reaches maximum strength at the age of 40, and decline gradually to the ages of 60-70. Thereafter, they decline more rapidly (Zhou et al. 1996). For long-term consequences, females aged 60 or older showed a higher risk of permanent medical impairment due to upper extremity fracture compared to younger females and males of the same age group (Gustafsson et al. 2014).

Crash severity from real life data can be defined in different ways. Residual intrusion is one measurement, but difficult to relate to impact force and vehicle deceleration. Therefore, the use of the change in velocity, delta-v, is more commonly used as a severity measurement. In NASS/CDS delta-v is calculated using a program called WinSmash, a two-step analysis where vehicle trajectory and damage are taken into consideration (Sharma et al. 2007). In the case of an intersection crash, both vehicle trajectories and intrusion profiles are entered into the calculations. Based on this information delta-v in the longitudinal and lateral directions, as well as the total delta-v, are calculated for both vehicles, and listed in the NASS/CDS database. It has been shown that the WinSmash calculator overestimated delta-v by 13% for car-to-car crashes compared to delta-v based on EDR data (Johnson and Gabler 2014). The WinSmash predictions were found to be more accurate for LTV-to-car crashes.

In Study I NASS/CDS data for 1994-2006 was analyzed in order to find all front seat occupants exposed to a nearside car-to-car impact. Only occupants 10 years old or older were selected, as well as cars manufactured 1980 or later. A nearside impact was defined as having a principal direction of force (PDOF) from 2-4 o’clock (passengers) and 8-10 o’clock (drivers). The sample consisted predominantly of cars without side airbags (98%). The NASS/CDS data was weighted to represent a national (US) estimate of nearside car-to-car crashes 1994-2006.

Crash exposure over lateral delta-v was plotted for the entire sample as well as stratified for non-senior and senior occupants. The empirical incidences for fatality (dead within 30 days post-crash) were investigated for the three occupant groups (all, non-seniors, and seniors). Gamma distributions were fitted to the empirical incidence to present the distribution of fatal injuries with respect to lateral delta-v. From the empirical incidence of fatal injury, and the number of exposed occupants, risk curves were derived.

To adjust the sample to represent a vehicle fleet equipped with side airbags, and thereby understand how to reach a 30% risk reduction of fatal injuries (McCartt and Kyrychenko 2006, Kahane 2007), a hypothetical airbag model was designed. The model, consisting of side airbag protection level θmax over
lateral delta-v is shown in Figure 6. For delta-v dependency, the model was based on the observation that when impact severity is low the airbag will not deploy until a given delta-v, denoted A. At high crash severity above delta-v, denoted C, the airbag will no longer have any mitigating effect due to vehicular structural behavior. These observations provide a start and end point for the airbag protection level as a function of delta-v, denoted $\theta(v)$. Due to legal and rating procedures at certain impact speeds, and with varying occupant sizes, it was assumed that the airbag has a constant maximum risk reducing effect, i.e. protection level $\theta_{\text{max}}$, from delta-v A to delta-v B, after which it decreases linearly (assumption based on observations from internal sled tests), to delta-v C.

In Study I, delta-v A was set at 10 km/h. Delta-v B was set at 30 km/h based on observations from FMVSS 214 and US NCAP tests. Due to the lack of information regarding delta-v dependency and airbag risk reduction in a delta-v above legal and rating tests, three delta-v Cs (C1, C2, and C3) were investigated. For the end points, C1-C3, delta-v 45 km/h, 55 km/h and 65 km/h, were assumed. With these constraints, the protection level, $\theta_{\text{max}}$, in the delta-v interval A-B, can be adjusted to provide an overall fatality reduction of 30%. Three values of delta-v C result in three different protection levels, $\theta_{\text{max}}$1-3. Hence, three models (Model 1-3), all giving a 30% side airbag fatality reduction, were evaluated.

![Figure 6. A hypothetical model of side airbag effectiveness.](image)

The hypothetical airbag models, representing 30% overall reduction of fatalities, was applied to the real life fatality incidence for the total NASS/CDS sample as an illustrative example of how currently established side airbag effectiveness would change the incidence of fatal side impact crashes in the field data, considering 100% implementation of side airbags. The total number of fatalities, $N_d$, is the integral over delta-v of the incidence of
fatalities at delta-v=v, I(v). The incidence can also be expressed as the product of exposure E(v) (i.e. the number of crashes at delta-v=v), and the risk of death R(v). Assuming a total effectiveness of 30% in fatality reduction provides a reduced number of fatalities \( \hat{N}_d = 0.7 \, N_d \). This is the result of a reduced risk of death applied to the unchanged exposure E(v). The effectiveness, sometimes called benefit, of a restraint system can be written as \( \text{Eff} = \frac{N_d - \hat{N}_d}{N_d} \). In the same way, the protection level, \( \theta(v) \), of a restraint system, at a given delta-v, can be written as \( \theta(v) = \frac{R(v) - \tilde{R}(v)}{R(v)} \). See Eqs 1-3.

\[
N_d = \int_0^\infty I(v)dv \quad \text{where} \quad I(v) = R(v)E(v) \quad \Rightarrow \quad N_d = \int_0^\infty E(v)R(v)dv \quad \text{Eq. (1)}
\]

\[
\hat{N}_d = \int_0^\infty \tilde{R}(v)E(v)dv \quad \text{Eq. (2)}
\]

\[
\text{Eff} = \frac{N_d - \hat{N}_d}{N_d} = \frac{1}{N_d} \int_0^\infty (R(v) - \tilde{R}(v))E(v)dv = \frac{1}{N_d} \int_0^\infty \frac{R(v) - \tilde{R}(v)}{R(v)} I(v)dv = \frac{1}{N_d} \int_0^\infty \theta(v)I(v)dv \quad \text{Eq. (3)}
\]

From the final integral in Eq. (3), it follows that maximum effectiveness is reached if \( \theta(v) \) is large when I(v) is large. In other words, the effectiveness of the restraint system is maximized if the airbag is optimized for delta-v at which most occupants are fatally injured, i.e., where the incidence is high.

To evaluate future enhancement of side airbag protection the hypothetical airbag models were used as references and the protection level (\( \theta_{\text{max}} \)) and delta-v were increased 20%, respectively, and in combination. The new fatality reduction for each of the three calculations was compared to the reference 30% risk reduction for the total sample, non-senior and senior group to evaluate the effect of respective improvements.

**Potential of AEB in Intersection Crashes**

This section describes how to apply the dose-response model to the results from Study I as a means of evaluating possibilities for crash avoidance and mitigation by intersection AEB. This evaluation is an addition to the individual studies in order to answer the research question, and to contribute to the overall aim of the thesis.

In Figure 7 the exposure of nearside car-to-car crashes, as well as fatal incidence and the injury risk from Study I, is presented. For an AEB system the exposure will change due to braking, and the curve will move to the left. As a consequence of the shift in exposure incidence will be reduced.
Figure 7. Left y-axis: Gamma distributions as a function of lateral delta-$v$ for exposure ($E$) and incidence ($I$) of nearside car-to-car crashes from Study I (older cars without side airbags). Right y-axis: Occupant injury risk ($R$) as a function of lateral delta-$v$.

However, the exposure, incidence and injury risk derived for fatal nearside car-to-car crashes in Study I was derived from crashes with older cars without side airbags. By applying different models of side airbag efficiency representing 30% fatality reduction, the incidence e.g. response, was adjusted to predict a fleet of side airbag-equipped cars. Based on crash tests performed at high impact speed airbag Model 2 ($C=55$ km/h) is assumed to be the most representative model (Sunnevång et al 2010). Introducing the side airbag according to Model 2 results in a shift of the fatal injury risk according to Eq. (4).

$$Risk\ (SAB) = \frac{Incidence\ (SAB)}{Exposure\ (no\ SAB)}$$  \hspace{1cm} Eq. (4)

The adjusted incidence curve, using Model 2 (presented in Study I), and denoted Incidence (SAB), is therefore used for evaluating opportunities by AEB in side crashes (Figure 8). As lateral delta-$v$ was used as a measurement of crash severity in Study I, and an AEB system reduces impact speed, it was assumed that impact speed was twice the lateral delta-$v$. Since the study included passenger cars only, similar masses of the bullet and target vehicle were assumed.
In an intersection crash there are three ways AEB can be used to avoid a crash. First, the target vehicle can brake, and thus avoid being struck in the side by the bullet vehicle. Second, the bullet vehicle can decelerate for a certain time, and thus avoid the crash, or mitigate crash severity. Third, both vehicles brake, and avoid or mitigate the crash. In the present thesis the first two scenarios are addressed (illustrated in Figure 9).

Assuming a target vehicle equipped with AEB, Target\textsubscript{AEB}. A 45\% effectiveness means that in 45\% of the conflicts the struck vehicle would have braked to avoid a crash (Sander 2016). The effectiveness of a target vehicle equipped with AEB can be calculated according to Eq. (5) and the adjusted incidence according to Eq. (6).

\[
Eff (Target_{AEB}) = 1 - \frac{Incidence (Target_{AEB})}{Incidence (SAB)}
\]

\[
Incidence (Target_{AEB}) = (1 - Eff(Target_{AEB})) \times Incidence (SAB)
\]
To evaluate the effect of a target vehicle being equipped with AEB the following assumptions were made:

- Since the crossing point was not reached at the same time, 45% of the crashes in Study I could have been avoided.
- Ideal sensor performance (Field of view, lighting conditions, etc.), and for obstructed vehicles, V2X communication (wireless vehicle communication to other cars or infrastructure).

A bullet vehicle equipped with AEB, Bullet\textsubscript{AEB}, would brake with a given deceleration at a given time before the crash, TTC (time to collision). Brake application will, in some crashes, avoid the crash by bringing the bullet vehicle to a complete stop before impact. For the remaining crashes the impact speed will be reduced. As a consequence the exposure curve will change. The incidence for an AEB-equipped, bullet vehicle, can be calculated according Eq. (7), and the effectiveness of the system according to Eq. (8).

\[
Incidence (Bullet_{AEB}) = Exposure (Bullet_{AEB}) \times Risk (SAB) \quad \text{Eq. (7)}
\]

\[
Eff(Bullet_{AEB}) = 1 - \frac{Incidence (Bullet_{AEB})}{Incidence (SAB)} \quad \text{Eq. (8)}
\]

Based on the situation, and driver comfort, different levels of braking can be applied. In this thesis a standard AEB level (as in current rear end AEB systems) was used, as well as a higher brake level (AEB+) that could potentially be used when a crash is unavoidable. The following assumptions were made for bullet vehicle AEB and AEB+:

- Ideal sensor performance (Field of view, lightning condition, etc.), and for obstructed vehicles, V2X communication
- Bullet AEB meaning constant, ideal braking of 0.8g at TTC=0.5s
- Bullet AEB+ meaning constant, ideal braking of 1.5g at TTC=0.5s

**Injury Distribution**

In study II NASS/CDS was queried to investigate the injury distribution and injury mechanisms for side airbag-equipped vehicles where the nearside occupant sustained at least one AIS2+ injury. NASS/CDS data between 2000 and 2012 was searched to extract all side impacts with belted occupants in modern vehicles (MY>1999). Rollovers were excluded, and only front seat occupants above 10 years of age were included. Occupants from this sample, seated adjacent to the intruding structure (nearside), and protected by at least one deployed side airbag, were studied case by case.
The case-by-case study was performed to gain a more detailed understanding of occupant injuries in terms of frequency and associations between injuries. Twenty-three injured body parts were identified as recurring in a trial study, and therefore, selected for further analysis in all 228 cases. For almost 50% of the cases in this study, either delta-v or information regarding intrusion was missing from the NASS/CDS files, making the relationship between injury and crash severity difficult to evaluate. As a complement residual intrusion, deformation close to the occupant, was also used as a measurement of severity in the crash.

A paired comparison was performed to evaluate the influence of occupant-to-occupant interaction in addition to nearside loading. The number of femur fractures, head injuries, and thoracic injuries for a single nearside occupant was compared to the number of injuries when a neighboring occupant was present in the crash.

**WorldSID Response Compared to Post Mortem Human Subjects**

In order to evaluate the WorldSID’s capability of reflecting human responses to oblique loading and low severity impacts, the dummy was compared to previously performed PMHS tests. Three PMHS were tested at the University of Virginia (Subit et al. 2010). The subjects were selected based on the absence of pre-existing unhealed fractures, lesions or other bone pathology, as confirmed by pre-test computed tomography (CT) analysis (Table 1). The subjects were obtained and treated in accordance with ethical guidelines established by the National Highway Traffic Safety Administration (NHTSA), and all testing and handling procedures were reviewed and approved by an independent oversight committee at the University of Virginia. The subjects were screened negative for infectious diseases and stored in a freezer (-15°C) until thawed at room temperature, 48 to 72 hours prior to the test preparation.

**Table 1: Summary of subject characteristics.**

<table>
<thead>
<tr>
<th>Subject id</th>
<th>Subject #</th>
<th>Age (year)</th>
<th>Weight (kg)</th>
<th>Stature (cm)</th>
<th>BMI (kg/m2)</th>
<th>Cause of death</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>427</td>
<td>79</td>
<td>79</td>
<td>181</td>
<td>24.1</td>
<td>Failure to thrive*</td>
</tr>
<tr>
<td>S2</td>
<td>420</td>
<td>59</td>
<td>93</td>
<td>180</td>
<td>28.7</td>
<td>Stroke</td>
</tr>
<tr>
<td>S3</td>
<td>430</td>
<td>74</td>
<td>47</td>
<td>173</td>
<td>15.7</td>
<td>Lung cancer</td>
</tr>
</tbody>
</table>

*No additional information provided*
For a comparison of side impact responses between the WorldSID and PMHS beyond the scope of ISO/TR9790, the WorldSID 50th percentile was successively impacted at low (1 m/s) and high (3 m/s) velocities using a constant-velocity impactor setup as previously described and used for PMHS evaluation by Subit et al. (2010). The WorldSID response in comparison to PMHS is presented in Studies III and IV. The reasoning behind the impact speeds was that low severity represents a low speed, non-injurious, crash as well as the loading from a pre-triggered side impact. The high velocity was considered in the same range as occupant loading in a modern vehicle subjected to a rating crash test.

As a straightforward attempt to relate the loading severity of the constant-speed localized impactor tests to dummy loading in a car crash, spine velocities (average of T1 and T12) in previously performed crash tests reported by Sunnevång et al. 2010 were retrieved and compared to the spine velocity in the WorldSID impactor test results (Study IV). A set of older cars (mid-size sedan MY 1998) represented the pre US NCAP vehicle fleet, and a modern US NCAP compliant set of vehicles (mid-size sedan MY2009) represented the current vehicle fleet.

The subjects were impacted at three levels on the upper body, and at three angles: 0° (lateral), +15° (posterolateral) and -15° (anteraolateral). For all impact directions the stroke length was at least 80 mm, and each test was repeated twice. The dummy was seated on a rigid chair designed to approximate a typical occupant position in a standard car seat and impacted to the left side (Figure 10).

Figure 10. WorldSID positioned on a rigid seat with the impactor targeting the shoulder (left), and definition of the impact levels relative to the landmarks on the WorldSID structure (right).

The WorldSID was impacted at three levels: the shoulder, the upper thorax, and the mid thorax (Figure 10). The impactor force and displacement were
measured in the Y-direction (Figure 10). In addition to the WorldSID internal deflection measurements kinematic data was also collected by tracking the position of retroreflective spherical markers.

In order to compare with PMHS responses, “anatomical locations” on the WorldSID were selected for measurement to approximate the locations used for the PMHS tests reported by Subit et al. (2010). These included the head, spine, pelvis, shoulders, and ribcage (Figure 11). Additionally, markers were placed on the seat and impactor. The external deflection of the struck side of the ribcage was measured using the motion of the impactor and upper spine. The 3D motion of the impactor was also tracked during impact, in accordance with the upper spine coordinate system, and the Y-axis component of this motion was taken to be the lateral chest deflection (Study III). The displacement of the spine was defined as the y-displacement of the point on the spine and aligned with the impactor.

In a side impact, the occupant is exposed to loading from the intruding structure. The loading applied translates into chest deflection and spine displacement during impact. In Study IV the PMHS and WorldSID allotment between chest deflection and spine displacement was evaluated as a means to gain further insight into the WorldSID biofidelic response in high and low speed impacts.

**Crash Tests**

To validate findings from the field data, and to evaluate occupant injury risk for the head and thorax in rating procedures as well as at higher severity (than in 2016 rating procedures), a set of crash tests were performed in Study V. A comparison of older vehicles without side airbags with modern vehicles with airbags using the WorldSID was presented by Sunnevång et al. (2010). To further evaluate nearside occupant injury risk using WorldSID, including occupant-to-occupant interaction, additional tests were performed. Different
loading conditions were used as well as different bullet vehicles. The target vehicle was always a passenger car of different sizes, and the WorldSID 50%ile male was always the nearside occupant. Test configurations are shown in Table 2.

Table 2. Crash test matrix from Study V.

<table>
<thead>
<tr>
<th>Target</th>
<th>Bullet</th>
<th>Car-to-Car</th>
<th>SUV-to-Car</th>
<th>Euro NCAP</th>
<th>Euro NCAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact Car (MY 2009), 1130 kg</td>
<td>Test 2</td>
<td>Large Sedan, 1735 kg</td>
<td>SUV, 2250 kg</td>
<td>Test 6 &amp; 7</td>
<td>Test 8 &amp; 9</td>
</tr>
<tr>
<td></td>
<td>70 km/h</td>
<td>50, 50 km/h</td>
<td>32, 32 km/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Sedan (MY 2009), 1200 kg</td>
<td>Test 3 &amp; 4</td>
<td>Test 1</td>
<td>65, 65 km/h</td>
<td>Test 5</td>
<td>60 km/h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large Sedan (MY 2009), 1865 kg</td>
<td>80 km/h</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first four tests evaluated the WorldSID nearside response to high severity vehicle-to-vehicle crashes, representing the characteristics of fatal intersection crashes in Sweden where impact speed was found to be 70-80 km/h, and the residual intrusion approximately 350-500 mm (Sunnevång et al. 2011). The vehicle-to-vehicle tests were performed in a 90° impact aligning the bullet centerline to the middle of the target wheelbase. Impact speed was 65 km/h for the SUV impacts, and 70km/h and 80km/h for the car-to-car tests, respectively. The consumer rating tests including moving deformable barrier tests and oblique pole tests were performed to evaluate WorldSID 50th male response to the Euro NCAP 2016 protocol, except that the large sedan was impacted at 60 km/h instead of the specified 50 km/h (Euro NCAP 2015b).

In each of the crash tests the WorldSID 50th percentile male was seated on the struck side (nearside), and the WorldSID used in this test series was equipped with 12 two dimensional IR-Traccs’ (2D IR-Tracc); 6 on the left side, and 6 on the right. This design enables measurement of bilateral loading (deflection from the left and right side of the thorax). Due to limited availability of WorldSID dummies other crash test dummies were used representing the neighboring occupant. In the vehicle-to-vehicle tests, and the Euro NCAP test at 60 km/h, a THOR-NT was seated on the non-struck side, and in the Euro NCAP tests with the small sedan (AE-MDB and Oblique Pole) a EuroSID2 was seated on the non-struck side. In all tests the WorldSID and neighboring dummy were restrained by a three-point pre-tensioning (2 kN at the retractor) seat belt, and on the struck side an inflatable curtain and a seat-
mounted side airbag protected the head and thorax from the intruding structure. Since the vehicles tested as well as crash test configurations varied between tests, results were compared with respect to severity in terms of lateral delta-v and residual intrusion at the occupant position.

For injury assessment, WorldSID specific head and thorax injury risk curves (IRC) were used. The head injury criterion, HIC, was calculated, and the corresponding AIS3+ injury risk was derived using the IRC from NHTSA (1995). Peak deflection, measured by the IR-Tracc, and calculated viscous criterion, VC, on the inboard and outboard side was used as injury criterion for assessing AIS3+ thoracic injury risk. Injury risk was calculated using the IRC for a non-senior and senior occupant, derived by Petitjean et al. (2012). AIS3+ thoracic injury risks based on peak deflection were calculated for an occupant aged 45 and 67, respectively. For soft tissue thoracic injury based on VC, the injury risk for a 45-year-old occupant was calculated (Petitjean et al. 2009).

Results

Real-life Data Analyses

In Study I, the real life data analysis based on side impacts in the US between 1994 and 2006 showed that non-senior and senior occupants were equally exposed to side impacts. However, seniors were overrepresented in fatal injuries, and impact severity was lower for crashes resulting in fatal injury (Figure 12).

![Figure 12](image)

*Figure 12. Fatal incidence and injury risk for the total sample (left) as well as stratified into senior (dashed line) and non-senior (line) samples (right).*

Applying the three-airbag models to the incidence of fatal crashes for the total sample resulted in three levels of airbag protection as presented in Figure 13. However protection levels differed when applied to non-senior and senior groups, respectively.
Figure 13. Left y-axis: The three hypothetical airbag models for the total sample. All models resulted in 30 percent overall airbag effectiveness. Right y-axis: The new incidences for fatal injury calculated for each of the three models compared to the original incidence for the NASS/CDS sample without airbags.

For the non-senior occupants the hypothetical models showed high protection levels up to delta-v of 40 km/h. The protection level for senior occupants was lower when compared to the level for non-senior occupants.

The reduction of fatalities when the delta-v or airbag protection level, or a combination of the two, were increased, is shown in Figure 14. The results should be compared to the 30% fatality reduction, which represents the current side airbag protection systems. The maximum effectiveness of delta-v or airbag protection level is shown on the left.
Figure 14. Comparison of effectiveness (30 percent for current systems) with a 20 percent increase in delta-v compared to a 20 percent risk reduction, and thus an increase of the protection level, by combining the two approaches.

Potential of AEB in Intersection Crashes

In this section the additional evaluation (in addition to the individual studies), of AEB’s influence on results from Study I, is presented. For the target vehicle equipped with AEB the incidence of fatally injured occupants would change according to Figure 15.

Figure 15. Comparison of fatal incidence for airbag-equipped cars (grey), assuming 45% crash avoidance by target vehicle equipped with AEB (black).
By calculating a new delta-v for AEB-equipped bullet vehicles exposure will change and incidence will be reduced (Figure 16).

If the bullet vehicle is equipped with AEB, and braking by 0.8g is applied at 0.5s prior to crash (TTC=0.5), incidence would be affected, as presented in Figure 16. Crash avoidance and speed reduction would reduce the number of fatalities by approximately 70%.

With a higher braking level, AEB+ (1.5g), the exposure would change and incidence reduced according to Figure 17. Introducing the AEB+ would reduce the number of fatalities by approximately 95%.

As the above examples show, braking of the vehicle has a substantial effect on injury outcome. Braking of the target vehicle, by target vehicle AEB, prevents the crossing point being reached at the same time, and the crash is thereby avoided. Crashes can also be avoided by bullet vehicle AEB, and even if the crash cannot be avoided, speed reduction is of the utmost importance for injury outcome.
Injury Distribution

The NASS/CDS analysis in Study II showed that the senior group sustained at least one AIS2+ injury in approximately 90% of intersection crashes. The remaining 10% were due to loss of control. Most of the non-senior occupants were also injured in intersection crashes (70%), but had a larger proportion of loss-of-control crashes (25%), and a smaller proportion of other crashes (5%).

The most frequent injuries in nearside impacts were rib fractures, regardless of whether the occupant was senior or not. For the non-senior group the frequency of rib fractures, brain injuries, and pelvic fractures was similar, but for senior occupants rib fractures were the most frequent, followed by pelvic fractures and brain injuries.

Comparison of the odds ratios between the number of occupants who sustaining femur fractures versus head and thoracic injury, for one or two front seat occupants, respectively, showed a trend for the nearside occupant’s risk of head injury to decrease, and the risk of thoracic injury to increase, when a neighboring occupant was present. However, the difference was not statistically significant.

WorldSID Response Compared to Post Mortem Human Subjects

Time zero was set to when WorldSID was in contact with the impactor, intruding structure, or side airbag, showed that spine velocity for the impactor tests at 3 m/s was similar to the dummy response in the modern car-to-car test (Study IV). In the 1 m/s impact spine velocity was lower than what was observed in the crash tests (See Figure 18).

![Spine velocity comparison](image)

**Figure 18. Comparison of average WorldSID T1 and T12 spine velocity for impactor and crash tests.**
During the impacter tests shoulder peak force was similar for PMHS and WorldSID at 3 m/s (Study III). In contrast to the PMHS, where peak force decreased as impact location decreased to mid thorax, the WorldSID peak force was lowest at the shoulder and highest at mid-thorax. For the 1 m/s impacts, WorldSID peak force followed the same trend as in 3 m/s impacts, shoulder lowest, and mid thorax highest, but lower in magnitude. However, peak forces for the PMHS were similar in magnitudes regardless of impact location (Figure 19).

![Figure 19. Comparison of impacter force for WorldSID and PMHS in impacter tests.](image)

Impact direction did not affect peak force levels for the WorldSID. Neither did impact direction affect the external deflection measurement (Study III). External chest deflection for the WorldSID, measured at a 3 m/s impact, was slightly higher than for the PMHS, although within the spread of the three subjects tested. Lowest deflection was measured for shoulder impacts, and highest at mid thorax for both dummy and PMHS. At 1 m/s the WorldSID external chest deflection was significantly smaller than for the PMHS for all impact locations (See Figure 20).
In Study IV the difference in response between WorldSID and PMHS was further investigated. To better understand the response to the localized impacts at 3 m/s and 1 m/s chest deflection versus spine displacement was compared for WorldSID and PMHS. In the PMHS tests the ratio between chest deflection and spine displacement was found to be similar regardless of impact level, with higher chest deflection at 3 m/s than at 1 m/s impact. For the WorldSID impact location affected the ratio, as did the impact speed. Comparing WorldSID to PMHS results showed that at 1 m/s more of the impact energy was used to move the spine than in the PMHS, especially for the impact at shoulder level (See Figure 21).

**Crash Tests**

In the crash tests performed in Study V, peak chest deflection was always measured on the struck side at a lateral delta-v similar to NCAP severity. At a higher delta-v peak deflections on the inboard and outboard side were similar, and in some tests peak deflection occurred at the inboard side as the result of
interaction with the neighboring occupant. Outboard and inboard peak chest deflections are shown in Figure 22.

![Graph showing outboard and inboard peak chest deflections](image)

**Figure 22.** Outboard and inboard WorldSID peak deflection with respect to lateral delta-v.

For a 45-year-old the injury risk based on outboard peak deflection was below 10%, except for the SUV test with high intrusion (Figure 23). In the Euro NCAP tests the injury risk was below 5%. For a 67-year-old injury risk based on outboard deflection was found to be above 10% in one of the Pole tests, as well as in all other tests. Occupant-to-occupant loading resulted in notable injury risk for a senior occupant in the non-Euro NCAP tests.

![Graph showing AIS3+ thoracic injury risk](image)

**Figure 23.** AIS3+ thoracic injury risk based on outboard and inboard peak deflection for a 45-year-old occupant (solid bars), and a 67-year-old occupant (striped bars).
General Discussion

The aim of this thesis was to provide guidelines for improved side impact protection. With the development of advanced safety systems it is important to relate in-crash occupant protection to pre-crash countermeasures in order to identify areas to prioritize for improved safety according to the Safe System Approach and Vision Zero. Hence the integrated safety chain was used as the theoretical framework to point out cornerstones of the extensive area of side impact occupant protection.

Injuries, Injury Risk and Severity Levels

Since the introduction of side airbags, and the accompanied structural changes during the last years, the risk of sustaining a fatal or serious injury in a nearside crash has been reduced (McCartt and Kyrychenko 2007, Jakobsson et al. 2010, Stigson and Kullgren 2011, D’Elia 2013, Kahane 2014). However, serious injuries still occur, and senior occupants are overrepresented in accident data (Studies I and II). Due to the frailty and fragility of senior occupants the protection level of current side airbags could be different for non-senior occupants, as concluded in Study I. It has been argued that the risk-reducing effect is lower for senior occupants as compared to non-senior occupants, and that the side airbag could be a potential injury source for this population (Griffin et al. 2012). Based on the results in Study I it was concluded that to enhance side impact protection the protection level of the side airbag should be improved within current (2016) rating test severity, as well as to improve occupant protection at higher severities. Improving protection for higher severity levels does not necessarily imply developing airbags for higher impact speeds. As presented in the background there are infrastructural countermeasures, as well as AEB systems that can reduce crash severity. These countermeasures could be more efficient than an in-crash system, and, therefore, the results from real life data need to be put in a larger perspective using the integrated safety chain.

Shifting focus from fatal and serious injuries to moderate injuries (AIS2+) sustained in modern, side airbag-equipped cars, showed that head, thorax, and pelvic injuries were the most frequent, especially for senior occupants (Study II). These findings are in line with results from other studies where real life data was analyzed, stratified by age, for a mixed sample of airbag- and non-airbag-equipped vehicles (Ridella et al. 2012, Carter et al. 2014). Study II also concluded that the presence of a neighboring occupant tended to increase the risk of thoracic injury to the nearside occupant. This was due to sequential bilateral loading when the occupant was struck first on the outboard side by
the airbag and intruding structures, and then on the inboard side by the neighboring occupant. An additional side airbag on the inboard side has been shown to mitigate the loading for, and from, a farside occupant (Newland et al. 2008).

Summarizing the results of Studies I and II shows that although a risk reducing effect could be seen, the most frequent injured body regions in side airbag-equipped vehicles remains unchanged. Fatal accidents still occur at severity levels above current rating procedures (Study I, Sunnevång et al. 2011), and injurious crashes occur at severity levels within the current rating procedures (Study II). In both studies seniors were injured or killed at lower severities than non-senior occupants. Injury sources listed were side interior, A- or B-pillar, and for injurious cases, other objects such as trees and bullet hoods. This implies that although energy control and loading distribution has changed, resulting in fewer fatal injuries, the overall crash characteristics, injury mechanisms, and injury distribution, do not appear to have changed.

To evaluate nearside occupant risk of injury for varying crash severities and crash modes, the WorldSID AIS3+ injury risk was measured in crash tests performed at different impact speeds, as well as in different impact configurations (Sonnevång et al. 2010, Study V). In Study V it was shown that the AIS3+ injury risk to the head and thorax, measured by the WorldSID, was very low in the current (2016) rating procedures, when IRC for a 45-year-old occupant was applied. Using risk curves representing a senior occupant (67 years old in Study V based on published IRCs) show that at delta-v above 30 km/h, intrusion above 350 mm, the AIS3+ thoracic injury risk was above 10% (Figure 23), based on outboard deflection. Above delta-v 35 km/h the thoracic AIS3+ injury risk due to occupant-to-occupant interaction was found to be above 20%. With today’s side airbag protection level, car-to-car side crashes above an impact speed of 60 km/h should be avoided through other countermeasures. The injury risk obtained from interaction with the neighboring occupant also implies that WorldSID is suitable for assessment of injury risk due to occupant-to-occupant interaction, and that this loading condition needs to be taken into consideration for future enhancement of side impact protection (Study V).

The variation of tests included in Study V points out the variation in occupant loading due to vehicle compatibility and structural behavior, and as a result, a variation in delta-v and intrusion. This variation is also present in the accident data, but it is difficult to approximate real life conditions with one laboratory test setup. To improve overall occupant protection in side crashes, head injuries, rib fractures, and pelvic fractures need to be assessed using a
biofidelic crash test dummy with biomechanical limits based on occupant injury risk from real life data.

In the WorldSID/PMHS comparison performed in Studies III and IV two severity levels were evaluated. One, as the representative of a consumer rating test (3 m/s), and one low severity crash, or representing a pre-crash triggered side airbag, (1 m/s). The WorldSID showed a potential for reflecting PMHS deflection and kinematics at the higher severity level, including oblique loading, but not at the lower severity (Study III). For low severity levels the WorldSID design tends to over represent spine displacement, resulting in significantly lower chest deflection compared to the PMHS (Study IV). At 3 m/s the ratio is similar between PMHS and WorldSID, with slightly higher degrees of spine displacement at shoulder impact. Based on these results it is important to know the severity levels for which the dummy is used, and in what range of impact severities dummy biofidelity is evaluated. With available thoracic injury risk curves for different ages, as well as the ability to handle oblique loading, there are possibilities for designing more advanced protection systems. However in low severity impacts (as the 1 m/s impactor tests are considered non-injurious) deflection could be underestimated, based on one PMHS compared to the WorldSID (Study IV).

In Study V the WorldSID assessed injury risks comparable to what was expected from the field data (Study II). The WorldSID also showed similar force and deflection responses to the PMHS in the high speed impactor tests (Studies III and IV). The ability to measure oblique loading, and loading due to occupant-to-occupant loading provides further opportunities for improved side impact protection using WorldSID as an evaluation tool.

**Analysis Using the Integrated Safety Chain**

Crash avoidance, mitigation, and controlled energy transfer to the occupant needs to be evaluated on a systemic level, and the integrated safety chain is one available method. Non-compliance to speed limits is one of the greatest challenges in reaching set targets of reduced traffic injuries. To enforce compliance with speed limits, speed cameras offer one solution. Replacing traditional intersections with roundabouts, and supporting infrastructure design is another. For speed control and intersection support systems, smart infrastructure communication with the vehicle, or vehicle-to-vehicle communication, could be used in the future. All countermeasures should, however, ensure that in the event of a crash the occupant injury risk is below the set threshold based on biomechanical tolerance.
There are several systems in vehicles with different levels of technical readiness that could be employed to reduce the number of side crashes. Depending on the system, they act in different phases of the integrated safety chain. Focusing on the driver, health monitoring through vital sign measurements can prevent incidents due to illness such as cardiac failure or hypoglycemia. Driver monitoring systems can already detect driver attention, and if the driver’s eyes are on the road. Such systems can determine a level of fitness to drive, which enables adaption vehicle support systems such as warnings and interventions. All these countermeasures can be evaluated using the integrated safety chain framework.

**Nearside Crashes in the Integrated Safety Chain**

The following section presents a demonstration of how to apply the integrated safety approach on side crashes, particularly by replacing intersections with roundabouts, implementation of an intersection assist system, introduction of intersection AEB (0,8g), AEB+ (1,5g), and improved side airbag performance (Figure 24).

![Integrated Safety Chain Diagram](image)

*Figure 24. Countermeasures for side impacts used to demonstrate the integrated approach for nearside crashes.*

To assess the injury-reducing effect of the presented countermeasures accident data from a representative sample should be used. In this example the 12354 AIS2+ injured occupants from Study II are used for demonstrating the application of the theoretical framework. Of the 12354 nearside injured occupants 8793 occupants were injured in intersection related crashes. By including risk reduction as presented in other publications the overall reduction of injured occupants can be evaluated, as shown in Figure 25. It should be noted that in this demonstration countermeasures are evaluated independently. For a full assessment using the integrated safety chain the altered characteristics of each phase of the chain should be taken into
consideration. This was not possible with the data available for the present analysis.

Starting with deviation from safe driving replacing intersections with roundabouts and thereby controlling speed would reduce the total number of crashes, as well as avoid or mitigate those resulting in injuries. Based on results from previous studies it can be assumed that roundabouts reduce injurious intersection crashes by 70% (Persaud et al. 2000, Gross et al. 2014).

For the remaining intersection crashes, in roundabouts or in remaining traditional intersections, an intersection assist system informing the driver when approaching an intersection, showing a safe gap, or highlighting traffic signs for yield or right of way, could be effective. There is no established effectiveness for such systems on the road, but could be comparable to blind spot detection, or monitoring systems showing a 5-15% reduction of injurious crashes (IIHS 2015a, 2015b). In the present example a 10% reduction is assumed from an intersection assist system.

In a critical situation, as well as when a crash is unavoidable, an AEB system could prevent or mitigate a crash. An additional analysis of the accident data from Study I was used to show the potential of an intersection AEB system, using two braking levels (Figure 16 and Figure 17). Applying the reduction of delta-v from the AEB and AEB+ on the injury risk function, and then calculating the new incidence, showed that 70-90% of fatalities could be prevented depending on the brake level. In the demonstration of the integrated approach this effectiveness is applied to the total population in Figure 25, where AEB is used in a critical situation, and AEB+ when a crash is unavoidable. The above examples were demonstrated for the entire dataset from Study I. However, the distribution of fatal crashes was different when divided into a senior and non-senior group. Full implementation of well performing AEB systems is therefore assumed to avoid a larger proportion of the crashes in which senior occupants are injured or killed. It should be noted that the AEB benefit calculated in this thesis was based on fatal accidents, unlike previous findings on intersection AEB, which focused on all crashes regardless of injury outcome (Sander 2016). The high benefit found, based on this data sample (70-90%), implies that AEB could have a greater effect on crashes with severe injury outcome.

Using injury risk functions developed for senior occupants when developing and evaluating side airbag protection level will most likely increase. Previous studies on pre-crash deployed seat, airbag and belt systems in side impact have shown a 20 % overall injury risk reduction using the EUROSID2, and up to 90% reduction of thoracic injury risk using the WorldSID dummy.
Hierlinger et al. 2016, Pipkorn and Sunnevång 2016). The present analysis estimated a 20% benefit for the aforementioned actions, which is believed to be somewhat conservative.

Figure 25. Example of different countermeasures for nearside crashes in the integrated safety chain.

As shown in Figure 25 the above mentioned countermeasures would result in a substantial reduction of injured nearside occupants. Even if the absolute
levels of benefit are crude examples, based on different data samples, the example demonstrates how an integrated approach can be used to identify effects from different countermeasures improving side impact safety.

Following the recommendation to limit travel speed to 50 km/h at places where vehicle trajectories cross requires good infrastructural design. According to the EuroRAP rating roundabouts could allow speeds above 50 km/h, since the design reduces the speed to acceptable levels, while maintaining traffic flow. Lateral displacement when entering an intersection must be designed to achieve the desired speed reduction. Standardized roundabout design limiting speed and motion of the vehicles, will also lead to more standardized crash scenarios for the remaining crashes, which is easier to reflect in consumer rating. Roundabouts will serve as a countermeasure for controlling impact energy, and hence occupant loading. In conjunction with, or regardless of, roundabouts, automated emergency braking will have a substantial effect on side crashes. If both vehicles were equipped with this feature, a large amount of crashes could be avoided. As shown in Figure 16 an ideal AEB system could reduce delta-v by approximately 10 km/h, which represents a 20 km/h lower impact speed. With a 50 km/h speed limit where vehicle trajectories cross, such a system would reduce the impact speed to 30 km/h. Keeping the restriction on a survivable level at the impact speed of 50 km/h could allow the speed limit to be increased to 70 km/h in situations where no vulnerable road users are present.

Even if electronic stability control reduces a large number of loss-of-control crashes these types of crashes will still occur, resulting in high intrusion levels. Although less frequent, these need to be considered for the in-crash protection system. Improving the side airbag protection level in high severity crashes would also have an effect on impacts with heavy goods vehicles. These crashes are not covered in the present thesis. Pre-triggering of airbags inside the compartment or outside of the vehicle’s side can reduce occupant loading to the head, chest, and pelvis. However, pre-triggered systems need to be evaluated using the WorldSID, and preferably also using PMHS or human body model simulations, since loading from the pre-triggered system might be different than what the dummy is validated for.

**Improved Protection for the Remaining Unavoidable Crashes**

Once beyond the point of no return, that is, when a crash is inevitable, injury mitigation is imperative. Not only from societal, but also from a consumer perspective. In a future transport system, with integrated safety features and fully automated vehicles that allow occupants to engage in tasks other than
driving, moderate injuries (AIS2+ and injuries leading to medical impairment) will be unacceptable. If a crash occurs, the injury outcome should be low, regardless of the occupant’s age, gender, or stature.

Intersection crashes involving senior occupants should be one of the focuses for enhanced side impact occupant protection. The focus on senior occupants is recommended due to the continuously increasing global life expectancy (Roser 2016). In 2030 it is estimated that 20% of all drivers will be above 65 years old (Lyman et al. 2002). There is no universal solution to avoid all intersection crashes, but with speed reduction and energy control due to infrastructural design and AEB for intersections, a substantial portion of these crashes can be avoided. More importantly, in the remaining crashes crash severity will be lower, and thereby survivable. Hence there is a need for improved protection within this severity range.

Loading from the intruding structure, as well as from a neighboring occupant, should be evaluated. There is also a need to identify and assess low severity injuries resulting in long-term, but not life-threatening, medical impairment for future cars with higher levels of automation. Taking into account all of the above, and a more diverse population than in current ratings (focusing on the mid-size male), could result in multiple test modes to ensure acceptable injury risk to occupants in a variety of impacts. It should be pointed out that virtual simulations using human body models could be used for such an evaluation.

Biofidelity evaluations of the WorldSID 50 percentile male compared to the currently (US NCAP), and previously (Euro NCAP) used EuroSID2 dummy, have shown that the WorldSID is more humanlike in its responses (Compigne et al. 2004, Yoganandan and Pintar 2008, Ruhle 2009). The kinematic behavior in farside impacts has also been evaluated and shown to better represent a human response compared to previous dummies (Fildes et al. 2002, Pintar et al. 2007). The comparison of WorldSID and PMHS, as in Studies III and IV, support the previous findings, although the WorldSID response in the low speed impact differed compared to a PMHS impacted at the same speed. Hence, rather than focusing on high severity crashes for restraint systems and biofidelity evaluations there is a need to understand human responses at lower severities, especially when addressing senior occupant safety due to their fragility and frailty, but also to find reliable injury criteria for less severe injuries leading to long-term medical impairment.

With nearside occupant protection currently only evaluating struck side loading, there is a need for assessing injuries due to occupant-to-occupant interaction, which was demonstrated in Study V. Although argued that a passenger presence contribute to an overall injury risk reduction for senior
driver crash involvement (Bédard and Meyers 2004, Braitman et al. 2014), a passenger becomes a contributing factor to the injuries sustained by elderly occupants in side crashes.

**Implication of Results**

Since it is difficult to prevent vehicle trajectories to cross within the traffic system, side impacts remain a common crash type, leading to fatal and severe injuries. By using an integrated approach to evaluate countermeasures it was shown that there are countermeasures capable of substantially reducing the number of crashes, decreasing crash severity, and thereby reducing the number of fatal and serious injuries.

By keeping the vehicle on the road with ESC a large portion of the impacts to fixed object and trees can be eliminated, reducing the median delta-v. Further development of current AEB systems to brake in an intersection, or roundabout crash, would reduce fatalities by up to 70%. Remaining crashes would occur at a lower speed, and with less impact variations than in current intersection crashes. With the aforementioned countermeasures the implication of increased crash severity in consumer rating tests to address injuries observed in the accident data should be revised. Focus should be on AIS2+ head, thorax, and pelvic injuries as well as injuries resulting in long-term consequences. Evaluation of occupant protection in these future scenarios could be performed using available regulation and rating procedures with slight modifications. Maintaining current severity levels, there remains a need for variation of impact angle, impact location, and farside and occupant-to-occupant protection to ensure robust protection performance. In addition to age, occupant size and gender should be taken into account.

The WorldSID with demonstrated improved biofidelity, as well as injury risk functions representing a senior occupant, is a better option than the ES-2re for assessing nearside occupant injuries. With bilateral equipment it is feasible to evaluate loading to the occupant from the intruding structure as well as from a neighboring occupant; and improved biofidelity makes it suitable for assessing farside occupant protection. However, there is a need for both biofidelity evaluations at lower severities to address less severe injuries, and improved biomechanical knowledge of injury mechanisms leading to medical impairment, and injury risk functions for less severe injuries.
Limitations

In this section limitations of the thesis will be discussed. Limitations are included in the publications for each study, but only briefly discussed below.

In Study I, older cars (prior to FMVSS 214), cars with side airbag (>2%) and unbelted occupants were included to collect as large a data sample as possible for investigating the age factor. Results should be considered as an average of the time period. The hypothetical model was created to evaluate the potential effect of adjusting the sample to a modern airbag-equipped fleet. In Study II, considering less severely injured occupants in side-equipped vehicles, the sample size was too small to statistically derive injury risk functions with respect to crash severity. There is a substantial portion of cases in the NASS/CDS data with missing information on crash severity. Hence, intersection AEB evaluation was performed using the data from Study I. For cases with a calculated delta-v it should be noted that an over-estimation of delta-v was found when comparing NASS/CDS cases with a Winsmash generated delta-v compared to EDR data (Johnson and Gabler 2014).

In Study II and III the three PMHSs were tested repeatedly to limit the effect of inter-subject variability. Palpation after each test was used to check for rib fractures, but it was not possible to determine in which test the exact injury occurred. Another limitation to these studies was that only one PMHS was impacted at the lower severity (1 m/s). The same subjects were impacted at the higher severity on the opposite side, and responses were similar to the two other subjects impacted in the same configuration. Hence the subject was not considered an outlier.

In study V the limited availability of a second WorldSID, and hence use of EuroSID2 and THOR as the neighboring occupant, was a limitation. If a second WorldSID had been used as the farside occupant, injury risk to that occupant would have been estimable, and related to the nearside occupant risk. The occupant-to-occupant interaction would also have been similar in the different tests.

To fully explore side impacts using the integrated safety chain countermeasures should be evaluated as dependent of each other. American accident data was used in Studies I and II. This database does not cover long term consequences. Also, the traffic situation in the US differs from Europe, and to Sweden in particular. Intersections are larger in the US with higher speed limits, and although roundabouts exist, they are not as widely implemented. Intersection crashes in the US occur in urban areas, while in
Sweden intersection crashes with fatal and severe outcomes occur mainly on rural roads with higher speeds than in urban areas.

**Future Research**

To assess side crashes with the integrated safety chain where countermeasures are linked, the dose response model needs to be updated with a large sample of crashes with modern cars, for which crash severity is well documented. Such a study should, however, take into consideration the bullet vehicle type, and only include side airbag-equipped vehicles, since structural improvements were often made in conjunction with the introduction of side airbags. Such a study should also take into account the limitations of using delta-v for a mixed fleet of bullet vehicles (Johnson and Gabler 2014).

Considering WorldSID as a valid tool for injury assessment in side crashes, the AIS3+ thoracic injury risk for a senior occupant in a nearside crash was found to be low in car-to-car crashes resulting in a delta-v below 30 km/h. Risk of head injury was also low except when the two occupants’ heads collided. (Study V). Therefore, there is also a need to develop AIS2+ risk functions for the WorldSID head and thorax to assess injuries at lower severities. It is believed that by preventing large rib cage deformations, fractures as well as lung injuries can be avoided. Fractures due to occupant-to-occupant interaction should also be evaluated. Hence, there is a need for investigating biomechanical tolerances for the thorax when loaded first by an intruding structure (or airbag), and then by a neighboring occupant.

**Conclusions and Recommendations**

Working with injury prevention, human tolerances constitute the limits of the transport system, and more specifically vehicle support and protection systems. Despite the introduction of side impact protection systems, injuries to the head, thorax and pelvis are still frequent (Studies I and II). Future focus for side impact injury mitigation should be on intersection crashes, improved occupant protection for senior occupants, and protection for and from the farside occupant. Based on accident data only, one conclusion is that the airbag needs to protect at higher severities than currently tested. However, instead of developing structures and airbags for high-speed crashes, it is important to consider alternative countermeasures, and hence the need for an integrated approach to side impacts.

Analyzing nearside crashes using the integrated safety chain shows that speed management through roundabouts is an efficient countermeasure, reducing
the number of injurious crashes as well as reducing variations in crash severity. In combination with an intersection AEB a large part of side crashes could be avoided or crash severity mitigated. Restraint systems should therefore be improved for both nearside and farside occupants, focusing on reducing injury risk for brain injuries, rib fractures, and pelvic fractures, within the severity levels of current rating procedures. Such a system could be designed using the WorldSID, and would benefit non-senior as well as senior occupants.

The WorldSID dummy reproduces humanlike responses in lateral and oblique impacts as shown in Study III. However, at low crash severity chest deflection could be underestimated, which should be considered when evaluating, for instance, pre-crash inflated side airbags (Study IV). Setting biomechanical injury risk levels using injury risk curves derived for senior occupants, and measuring bilateral deflection, provides opportunities for future enhancement of in-crash occupant protection in side crashes (Study V).

A holistic approach for side crashes, as outlined in this thesis, resulted in the following recommended guidelines for improved side impact protection:

- Develop intersection assist systems to support, alert, or warn the driver of a potentially hazardous situation.

- Implement intersection AEB systems for crash avoidance, and more importantly, injury mitigation.

- Implement infrastructural changes to reduce and control speed, as well as impact conditions, at intersections.

- Implement countermeasures for injuries due to occupant-to-occupant interaction.

- Improve occupant protection by addressing AIS2+ head, thorax and pelvic injuries for the senior occupant.
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“Whatever the problem, be part of the solution. Don’t just sit around raising questions and pointing out obstacles.”

— Tina Fey, Bossypants
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