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PRIORITIES AND POTENTIAL OF PEDESTRIAN PROTECTION

Accident data, Experimental tests and Numerical Simulations of Car-to-Pedestrian Impacts

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ABSTRACT

Pedestrian disability and fatality as a consequence of car crashes is a large global health problem. To introduce maximally effective car-based countermeasures it is important to understand which injuries are most common and from which car parts they originate. It is also important to focus on the most severe injuries resulting in disability or death. The aim of this thesis was therefore to determine priorities for and evaluate the potential of car-mounted safety systems designed to mitigate severe upper-body injuries (including disability and fatality) of pedestrians in car crashes.

Accident data was collected from two areas; severe (AIS3+) accidents in Dresden/Hannover in Germany and fatal accidents in Sweden. For the surviving pedestrians an estimate of long-term injury was performed using accident data-derived risk matrices of permanent injury. Results showed that 31% would sustain a permanent impairment of some kind and 5% would sustain a more severe impairment, where the head was most susceptible to severe impairment. The car front frequently caused leg injuries, which is addressed in current regulations. However, current legal tests do not address the most common upper-body injury source, the windshield, which was found to be the dominating cause of head injuries. Chest injuries, frequently caused by both the hood and windshield areas in the severe and fatal crashes in this thesis, are also unaddressed in legal tests. Children are most commonly head-injured from the hood area, which is addressed in current regulations. Further, regulations do not fully consider brain injury with the current head test methods. Therefore, in this thesis focus was on upper-body injury/source combinations not addressed in the regulations, that is, the head-to-windshield area and chest-to-hood/windshield areas, and the evaluation of brain injury in hood and windshield impacts.

Experimental head-to-hood component tests with succeeding brain simulations were performed to evaluate the influence of the under-hood distance and head impact speed. A hood designed to minimize linear head loading to acceptable injury levels was also found effective in reducing combined linear/rotational brain loading. Further, in full-scale car-to-pedestrian finite element simulations both a braking and deployable system alone proved efficient in reducing head and chest loading, and an integrated countermeasure of combining the two systems proved to increase the protection potential.

While current pedestrian countermeasures focus on the head-to-hood impact, this thesis recommends extending countermeasures to the lower part of the windshield and the A-pillars, and adding brain and chest injury assessment for both hood and windshield areas to effectively minimize disabling and fatal injuries. Since head impact location and head impact speed is dependent on the car design, the introduction of full-scale simulations in the test methods to determine impact conditions for experimental component tests is recommended. If the deployable countermeasures are combined with autonomous braking in an integrated system the most effective system is achieved. Auto-brake systems should, in high speed impacts, aim to reduce speeds to where the secondary countermeasures can effectively mitigate injury. Future pedestrian test methods should therefore evaluate how primary and secondary countermeasures interact.

LIST OF PUBLICATIONS

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

I. Fredriksson R, Rosén E and Kullgren A. *Priorities of pedestrian protection – A real-life study of severe injuries and car sources*. Accident Analysis & Prevention, Vol. 42 (6), pp. 1672-1681, 2010.[1]

II. Fredriksson R, Zhang L, Boström O and Yang K. *Influence of impact speed on head and brain injury outcome in vulnerable road user impacts to the car hood*. Stapp Car Crash Journal, Vol. 51, pp. 155-167, 2007.[2]

III. Fredriksson R, Shin J and Untaroiu C. *Potential of Pedestrian Protection Systems – A Parameter Study Using Finite Element Models of Pedestrian Dummy and Generic Passenger Vehicles*. Accepted for publication in Traffic Injury Prevention, 2011.[3]

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[1] Fredriksson designed the study with assistance from Rosén. Rosén performed the statistical analyses and Fredriksson performed the detailed case analyses. Kullgren assisted with design and analysis of long-term injury evaluation. The paper was jointly written by Fredriksson and Rosén.

[2] Fredriksson and Boström designed the study with assistance from Zhang and Yang. Fredriksson performed mechanical tests, and Zhang performed the numerical simulations. Fredriksson performed the analysis with assistance from Zhang and Boström. Fredriksson, primarily, and Zhang were the main authors.

[3] Fredriksson designed the study, with feedback from Untaroiu. Shin developed the models and performed the simulations under supervision from Untaroiu. Fredriksson performed the main part of the analysis and the manuscript was written by Fredriksson and Untaroiu.

CONTENTS

LIST OF ABBREVIATIONS

AIS	Abbreviated Injury Scale. See also Definitions.
CSDM	Cumulative Strain Damage Measure
CI	95% confidence interval
EEVC	European Enhanced Vehicle-safety Committee
Euro NCAP	European New Car Assessment Programme
FE	Finite Element
GIDAS	German In-Depth Accident Study
GTR	Global Technical Regulation
HIC	Head Injury Criterion
ISO	International Organization for Standardization
MPV	Multi Purpose Vehicle
ms	Millisecond (1/1000 of a second)
NHTSA	National Highway Traffic Safety Administration
PCDS	Pedestrian Crash Data Study
PMHS	Post Mortem Human Subject
SIMon	Simulated Injury Monitor
SUV	Sports Utility Vehicle
TBI	Traumatic Brain Injury
WAD	Wrap Around Distance. See also Definitions.
WG	Working Group

DEFINITIONS

50th percentile male	Average male, 50% of the male population is smaller.
95th percentile male	Large male, 95% of the male population is smaller.
A-pillar	The most forward car structure joining the hood/fender area and the roof. Also the side member of the windshield frame. See also Figure 1.
Abbreviated Injury Scale (AIS)	Single injury ranking with a scale of 1 to 6 representing 'threat to life' associated with a traumatic injury. 1=minor, 2=moderate, 3=serious, 4=severe, 5=critical, 6=unsurvivable
Child	In this thesis "children" are defined as persons 0 to 14 years of age (less than 15 years).
Component test	Test involving only one body part of the pedestrian.
Countermeasure	Safety system or protection system.
Full-scale test	Test involving full body of pedestrian and vehicle.
Hood	Outer car structure protecting the engine compartment. See also Figure 1.
Integrated safety	Combination of primary and secondary safety.
Primary safety	Pre-crash safety or active safety.
Secondary safety	In-crash safety or passive safety.
Senior	In this thesis "seniors" are defined as persons 65 years and older.
Severe injury	In this thesis defined as AIS3+ injuries; "serious" and more severe (including fatal), according to the AIS scale.
Wrap around distance	Measure from the ground surface up around the car contour to a selected point. Used both to define boundaries of a test zone or location of head impact. See Figure 1.

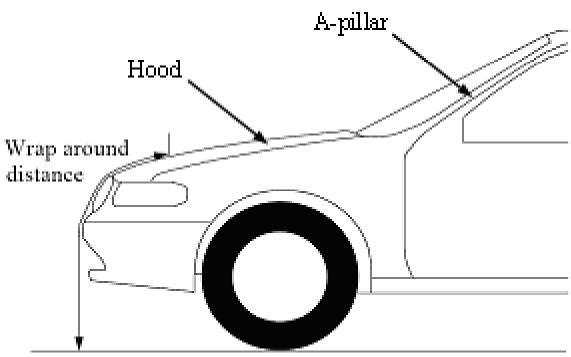

Figure 1. Wrap around distance, hood and A-pillar definition (based on EEVC, 1998)

1 INTRODUCTION

It is estimated that every year more than one million deaths are caused by road traffic injuries world-wide (Lopez et al., 2006), and in 2004 road traffic injuries were estimated to be the ninth leading cause of death globally (WHO, 2008). Road traffic accident deaths are estimated to almost double by 2030, and are estimated to be the fifth leading cause of death in 2030 (WHO, 2008). Today pedestrians account for about 12% of all road fatalities in the US, 15% in western Europe (EU-14[4], 19% for EU-19) and 33% in Japan (EC, 2010a, IRTAD, 2009, NHTSA, 2008). See comparison including examples of two extreme countries, Sweden and Mexico, in Table 1. In low-income countries, pedestrians account for larger proportions, for example 55% for parts of Africa (Naci et al., 2009). The high frequency of pedestrian fatalities in emerging countries leads to the fact that pedestrians make up a large proportion of global traffic fatalities. Naci et al. (2009) estimated that pedestrians account for more than 400 000 fatalities world-wide yearly. The high pedestrian fatality proportion in emerging countries can be due to the design of the road infra-structure and greater exposure to pedestrians. When countries develop, less people walk or cycle and start using cars. This decrease in pedestrian transport is not only positive in a public health perspective. It can also lead to other health problems, such as overweight (Bassett et al., 2008). It is also uncertain whether the actual numbers of pedestrians killed decrease when countries motorize. The US is considered a country with a low frequency of pedestrian fatalities. The pedestrian fatality proportion there is low compared internationally, usually explained by the fact that people walk less in the US. However, if you calculate pedestrian fatalities as a percentage of the population, Western Europe has a lower incidence rate than the US (see Table 1).

Table 1. Pedestrians killed in traffic accidents in 2007 (Mexico in 2000) (Sources: EC, 2010a, Híjar et al., 2003, IRTAD, 2009, Naci et al., 2009, NHTSA, 2008, WHO, 2008)

	Proportion of all traffic fatalities	Killed per 100 000 population
USA	12%	1.55
Western Europe	15%	1.15
Japan	33%	1.73
Mexico (2000)	54%	9.5
Sweden	12%	0.61
Global estimate	~35%	~6.6

4 EU-14 includes most western European EU countries, except Germany (incl. Belgium, Denmark, Greece, Spain, France, Ireland, Italy, Luxembourg, Netherlands, Austria, Portugal, Finland, Sweden, United Kingdom), EU-19=EU-14+ Czech Republic, Estonia, Hungary, Malta, Poland.

Further, a study of Chinese accident data showed that bicyclists and pedestrians had the highest disability incidence rate of road users (Fan et al., 2008). In a Swedish study more than 50% of injured pedestrians sustained long-term consequences (Falkenberg, 2008). There is a need to study the problem of pedestrian casualties in traffic and how they can be mitigated. This thesis aims to study pedestrian accidents focusing on vehicle and pedestrian interaction, and how the vehicle can be designed to minimize pedestrian casualties.

2 BACKGROUND

The following chapter is based on available pedestrian accident and experimental research predominantly based on the traffic situation in Europe, the US and Japan. This leads to the focus of this thesis on the pedestrian as the most frequently injured vulnerable road user and the passenger car as the dominating impacting vehicle. Thus far, detailed accident investigations and databases are not available for emerging countries. We know that vehicle distribution differs in many countries, with more light trucks and buses (Mohan, 2002), and many countries also have a larger proportion of other unprotected road users.

2.1 THE ROAD, VEHICLE AND ROAD USER

Three factors are important to fully understand a road traffic accident. The environment, the vehicle and the road user all contribute to accidents and determine their outcome (Haddon, 1980). Further, the accident can be divided into three parts on a time-scale; pre-, in- and post-crash. In each of these time events, the road, vehicle and road user are more or less influential factors important to consider.

The pre-crash phase describes the sequence leading up to the accident. In this phase the road design, weather, lighting conditions, vehicle condition, the pedestrian and driver behavior all interact, and if one or more of these parameters are faulty or unfavorable a dangerous situation can emerge. If the risk parameters are not minimized the dangerous situation can lead to an accident. Examples of poor road design could be sight obstructions or lack of safe pedestrian crossings. Poor vehicle brakes or lack of stability control (ESC; electronic stability control) are examples of vehicle factors. Distraction or alcohol intoxication of the driver or pedestrian, are road user factors that can contribute to risky situations. When the accident is unavoidable the vehicle impacts the pedestrian and the accident proceeds to the in-crash phase. During this phase vehicle design and speed are examples of vehicle-influencing factors, while pedestrian vulnerability is an influencing factor for the road user and surface rigidity for the road. Finally, in the post-crash phase rapid, emergency care can influence the outcome of pedestrian injuries.

This thesis will focus mainly on the road user (pedestrian) and the vehicle in the in-crash phase, that is, secondary safety, but will also, to some extent, study the influence of vehicle behavior in the pre-crash phase, then called primary safety. The post-crash phase will not be studied.

2.2 THE ACCIDENT

2.2.1 Influencing factors

In a vehicle-to-pedestrian accident the pedestrian is most commonly impacted from the side by the vehicle front (Okamoto et al., 2003, Yao et al., 2007, Yao et al., 2008), the typical accident situation being a pedestrian crossing a street. Passenger vehicles make up the largest proportion of vehicles involved in pedestrian accidents (SIKA, 2009). In

Europe the most common passenger vehicle front type is the sedan type with a low front and a relatively horizontal hood surface. In the US the sports utility vehicle type (SUV), with a higher front but similar hood and windshield design as the sedan, is a common vehicle type involved in pedestrian accidents (Longhitano et al., 2005). An emerging vehicle type is the multi-purpose vehicle (MPV) with a low front similar to sedan vehicles, but with a more inclined and often shorter hood surface and with a windshield angle similar to the hood surface angle.

Vehicle speed is an important factor influencing the outcome of the accident. Rosén and Sander (2009) presented an injury risk curve describing the relationship between vehicle impact speed and risk for fatal outcome for the pedestrian in a vehicle frontal impact. This was based on 490 accidents representative to Germany. The study showed that the risk for fatal outcome in a 50 km/h impact was twice as high as an impact at 40 km/h and 5 times higher than an impact at 30 km/h, indicating the importance of impact speed to determine outcome. Richards (2010) showed the same trend in the UK with a strong risk and speed correlation. The impact speed is influenced by the traveling speed and amount of pre-crash braking. By braking, an accident can be avoided or the impact speed largely reduced. One study reported that no braking or braking of less than 0.6 g was performed in about 50% of the accident cases (Hannawald and Kauer, 2004).

Older pedestrians are over-represented in severe and fatal pedestrian crashes with a higher injury and fatality risk (Henary et al., 2006, Loo and Tsui, 2009, Rosén and Sander, 2009). Henary et al. found in 552 US vehicle-to-pedestrian accidents that pedestrians 60 years or older had an almost threefold higher mortality rate compared to adults 19-50 years old. Loo and Tsui found, in a study of 4290 accidents in Hong Kong, a 3.6 times higher mortality rate for pedestrians 65 years or older compared to 15-64-year-old pedestrians. Rosén and Sander (2009) presented a pedestrian injury risk function where they concluded that age, along with speed, were the two most important parameters for risk of fatal outcome. The risk function was used to extract risk functions for different ages, compared to average adults, in Figure 2. Males are reported as more frequently involved in pedestrian crashes, but no gender difference has been found for the fatality risk (Rosén and Sander, 2009, Zhang et al., 2008).

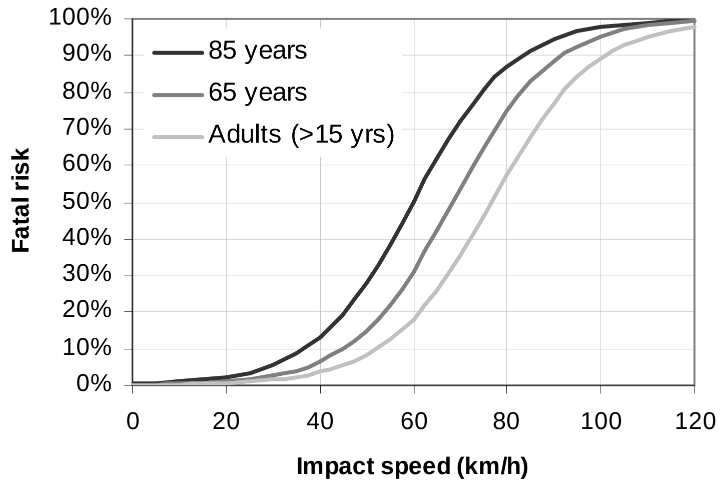

Figure 2. Fatality risk as a function of impact speed for different ages of pedestrians (based on data from Rosén and Sander (2009))

2.2.2 Injuries and injury sources

The most common method of defining the severity of injuries in traffic safety is the Abbreviated Injury Scale (AIS) with a scale from 1 to 6, where 1 denotes a minor, 2 a moderate, 3 serious, 4 severe, 5 critical and 6 maximum injury (AAAM, 2001, AAAM, 2005). The scale mainly predicts the risk of death and is not intended to predict the risk of disabling or long-term injuries. Most databases collect injury data shortly after the accident making AIS a suitable measure, while the study of long-term injury outcome requires larger resources and are seldom performed. Malm et al. (2008) developed matrices of risk for permanent medical impairment (RPMI) for different levels of impairment. It was based on long-term injury outcome for car occupants in traffic accidents, and risk was estimated for separate body regions based on the AIS level. With these matrices it is possible to estimate the risk of long term injury for a specific injury; e.g. an AIS 3 head injury is estimated to lead to a 1% impairment (lowest level) in 50% of cases (50% risk), while a thorax AIS 3 injury has only a 4% risk.

When including all injury severities the most injured body region in pedestrian-to-car impacts is the lower extremities, followed by the upper extremities and head (Roudsari et al., 2005). When focusing on more serious crashes, head and chest injury become more common while the proportion of leg and arm injury decreases. For serious and more severe (AIS3+) injuries, US studies show that the head is the most frequently injured body part followed by the lower extremities and torso (Longhitano et al., 2005, Zhang et al., 2008), while Japanese data shows that the lower extremities remain the most injured (Maki et al., 2003b). Studies of fatal accidents show that head trauma is the dominant single cause of fatal injury followed by chest trauma (Ehrlich et al., 2009, Maki et al., 2003b). Falkenberg (2008) showed, in a Swedish study, in a follow-up 1.5-6 years after the accident, that a majority of pedestrians seeking medical care after a car-to-pedestrian impact still suffered from the consequences at least 1½ years after the accident.

Real world data shows that head injuries in pedestrian accidents can be caused by linear or rotational loading or a combination of the two (Arregui-Dalmases, 2006). While only linear loading is used in current crash tests and regulations (see later section), rotational loading is an important contributing factor in brain injury outcome in traffic accidents (DiMasi et al., 1995, Gennarelli, 1985, Thomson et al., 2001), and since brain injuries are common in pedestrian crashes (Bockholdt and Schneider, 2003, Otte, 1999) one can expect rotational loading to be an important contributing factor even in pedestrian crashes. Arregui-Dalmases (2006) analyzed 173 US pedestrian crashes and concluded that in a majority of cases head injury was caused by combined linear and angular loading.

Compared with car occupants car impact locations are more widespread for pedestrians, impacting different structures depending on body height and impact speed. Some studies have investigated the frequency of vehicle injury sources in car-to-pedestrian crashes. The vehicle front, especially the bumper, is responsible for a majority of pedestrian injuries when studying all injury levels (Roudsari et al., 2005). When concentrating on more serious crashes, the windshield area becomes more frequent an injury source. Both German (GIDAS[5]) and US (PCDS[6]) data indicate that the hood is the major source of child head injury (Roudsari et al., 2005, Yao et al., 2007), and that the windshield area is the major source of head injury for both moderate and more severe injuries (Longhitano et al., 2005, Okamoto et al., 2003, Yao et al., 2008). Longhitano (2005) reported on the AIS3+ injury distribution and their vehicle sources, using the US PCDS data. It is important to note that while GIDAS is an ongoing activity, the PCDS data was collected between 1994 and 1998, and is thereby based on older vehicles. For cars the head-to-windshield impact was the most common of all injury/source combinations, followed by lower extremity-to-bumper. For the LTV vehicle type (light trucks and vans; to a great extent sports utility vehicles (SUV) and pickup trucks), the head-to-hood and torso-to-hood edge were the most common injury/source combinations.

The ground has been concluded to be a minor injury source compared to the vehicle. Studies using German and US representative data estimate the ground as the injury source at 17 to 31% (Liers, 2009, Otte and Pohlemann, 2001, Zhang et al., 2008). Further, data by Roudsari et al. (2005) indicates that injuries associated with ground impact result in lower severity levels than injuries (from the same body regions) associated to car sources.

Although several studies have reported on severe pedestrian injuries and their car sources, they are either based on older car designs or focused on one body region. No recent study was found that systematically investigated all severe (including fatal or disabling) injuries and their car sources. Study I and a Preliminary study presented in this thesis address these issues.

2.3 KINEMATICS

In a typical car-to-pedestrian crash, the bumper impacts the pedestrian's leg first with a subsequent impact by the hood's leading edge to the thigh, pelvis or chest region depending on vehicle and pedestrian size, followed by the pedestrian's upper body bending and rotating toward the hood surface with a thorax and shoulder impact to the hood or windshield, and the head impacting the hood or windshield surface (see Figure 3). In the subsequent motion the pedestrian is carried by the vehicle and most frequently falls to the ground in front of the vehicle. A pedestrian motion over the roof top with the pedestrian landing behind the car is uncommon and related to high crash speeds (Roudsari et al., 2005).

A pedestrian body versus hood sliding effect is visible in pedestrian tests with sedan-type cars. The pelvis slides up onto the hood surface after the impact of the thigh to the

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[5] German In-Depth Accident Study; accident in-depth database collecting on-site information from all traffic accidents with personal injury around Dresden and Hannover in Germany. From 1999 and on-going. Collects around 2000 crashes per year, of which approximately 400 are pedestrian crashes.

[6] Pedestrian Crash Data Study; implemented by the NHTSA as part of the Crashworthiness Data System for the years 1994 to 1998 to collect detailed crash reconstruction data on pedestrian crashes. Contains 552 pedestrian crashes.

hood leading edge. In twelve PMHS (post mortem human subject) tests performed, with three sedan-type cars and small to tall pedestrians (154-187 cm), the wrap around distance (WAD) to head impact was between 60-540 mm greater than the pedestrian stature in each test (Kerrigan et al., 2009, Kerrigan et al., 2007, Subit et al., 2008). This is related to sliding motions of similar distances. In similar tests with SUVs (two tests with tall pedestrians), with a higher hood leading edge, the sliding effect was less pronounced, with an 85-90 mm difference in WAD to stature (Kerrigan et al., 2009). In two tests with a small compact car a smaller WAD-stature difference was also measured; 20-80 mm for a short and tall subject (Subit et al., 2008). This indicates a higher WAD-to-head impact in collisions with sedan-type cars compared to collisions at same impact speed with vehicles with higher front-ends such as SUVs, or in vehicles with a more vertically inclined hood surface as in small compact cars.

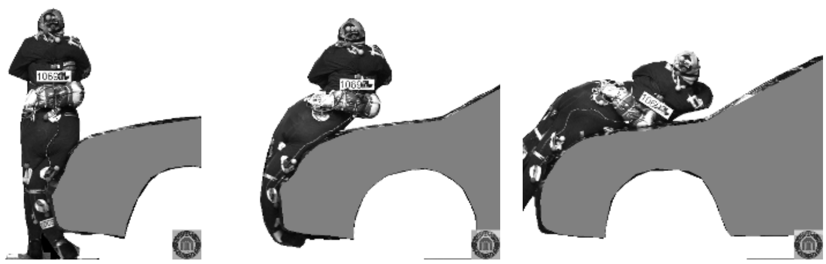


Figure 3. Pedestrian (PMHS) impact to car at 40 km/h (Kerrigan et al., 2007)

Accident data can also be used to investigate the sliding effect. Fredriksson and Rosén (2010) used German (GIDAS) accident data to derive a head impact WAD equation, where WAD depended on pedestrian stature and car impact speed. Using their equation to calculate the sliding effect (head impact WAD – body height) for three body heights, the following dependence on impact speed could be derived, see Figure 4.

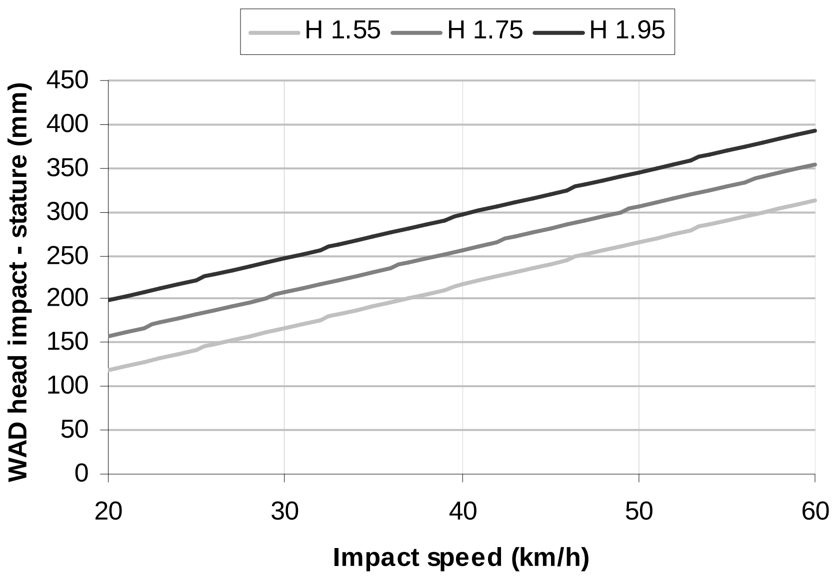


Figure 4. Difference (in mm) between head impact WAD and body height (stature) as a function of car impact speed ("sliding") for three pedestrian body heights (based on accident data from Fredriksson and Rosén (2010))

Head impact speed relative to the car can be both higher and lower than the initial car impact speed. Kerrigan et al. reported, in ten PMHS tests with sedan-type cars, head impact velocities ranging from 68%-130% of the car impact speed (Kerrigan et al., 2009, Kerrigan et al., 2008). There seems to be a trend that a higher impact velocity ratio is recorded when the head impact is to the windshield compared to the hood. Three of Kerrigan's tests with shorter pedestrians resulted in head to hood impact and their ratios ranged from 72%-90% while the seven windshield impacts ranged from 67%-130% with five of the seven cases above 100%. Masson et al. (2007) reported in four PMHS tests to two different sedan-type cars head/car velocity ratios ranging from 94% to 146%, all head impacts to the windshield.

Head impact times are dependent on car type, pedestrian stature and impact speed. Kerrigan et al. and Subit et al. reported, in their twelve tests with sedan-type cars at 40 km/h, head impact times ranging from 107-151 ms from first car-to-pedestrian impact, with the shorter times for shorter pedestrians. Four SUV tests have been performed with differing stature adult PMHS to measure head impact time (Kerrigan et al., 2009, Schroeder et al., 2008). The head impact times ranged from 90-116 ms. Subit et al. (2008) performed two tests with a small compact car and reported impact times of 91-94 ms for one short and one tall adult PMHS.

The influence of braking on kinematics has not been studied in detail. The changed impact location due to vehicle pitch and speed change could be important parameters to include. Such an analysis is better performed using detailed numerical pedestrian models where repeatability is controlled. This is performed in Study III.

2.4 TEST METHODS

2.4.1 Test tools

2.4.1.1 Full-body dummies and models

As early as the 1980's pedestrian specific test devices were developed. Aldman et al. (1985b) developed a rotationally symmetrical pedestrian dummy (Figure 5). In the early 2000's Autoliv and Chalmers University developed pedestrian dummies in adult and child sizes. The adult dummy, a 50^{th} percentile adult male, was based on existing frontal and side impact dummy parts with new parts designed for the lumbar spine and knee joints (Björklund and Zheng, 2001). The child dummy, equivalent to a 6-year-old child in size and weight, was based on a Hybrid III dummy with a redesigned neck, lumbar spine and knees (Renaud and Tapia, 2004, Renaud et al., 2005). Both dummies were tested at three different impact speeds and two car types and were compared to the Chalmers Madymo pedestrian model (Yang and Lövsund, 1987). The intention of these dummies was limited to study kinematics, not injury assessment. Honda and Gesac developed the Polar dummy, based on the Thor dummy (Akiyama et al., 2001, Akiyama et al., 1999). The Polar dummy was a more advanced pedestrian dummy, designed for both kinematic and injury assessment. The most important features were a flexible lower spine, deformable knee structures including ligaments, a deformable tibia with properties including fracture, and the Polar II version was validated against PMHS tests (Kerrigan et al., 2005a, Kerrigan et al., 2005b). The SAE pedestrian dummy task group developed a performance specification for an adult pedestrian dummy (SAE, 2009). The performance specification was based on PMHS tests using a mid-sized sedan and compared to the existing Polar II dummy in a report by SAE (2008). The Polar dummy is still under development, where new properties and injury assessment are under consideration (Akiyama et al., 2009, Okamoto et al., 2009, Takahashi et al., 2009).

Figure 5. Pedestrian dummies (from left): Aldman et al. rotationally symmetric, Autoliv/Chalmers child and adult dummies, Polar II

Numerical simulation is a good tool for reducing development costs, when nowadays even full-scale crash tests can be performed numerically. An advantage of simulations compared to physical tests is that the repeatability issue is eliminated. Scaling to different dummy sizes is more easily performed than in physical dummies. However, this requires a significant development effort for all included parts and an additionally detailed validation of all parts. Moreover, when models reach high detail level, high computer power is required. The Polar II was developed in a numerically finite element version by Shin et al. (2006). A finite element model of the Autoliv-Chalmers adult dummy was developed by Yao et al. (2011). Toyota developed a human body model, Thums, which was also presented in a pedestrian version (Maeno and Hasegawa, 2001, Snedeker et al., 2003, Snedeker et al., 2005). While the numerical Polar II has been validated, the Thums model is still in progress. When human body models are further developed, injury can be studied directly (e.g. rib fracture rather than chest deflection), and different properties can be set if studying, for example, the influence of age.

2.4.1.2 Component test tools

Pedestrian dummies are appropriate tools for research purposes, but are not optimal for legislative purposes. To use pedestrian dummies for legislative testing, a large range of sizes with small size increments would be necessary to assess all impact locations of a vehicle front, since the injury response is sensitive to impact location in pedestrian impact. Further, the long duration, pedestrian impact event makes repeatability challenging. EEVC concluded this in their WG10 and WG17 reports (EEVC, 1994, EEVC, 1998), in which they proposed impactor test methods. They proposed a lower legform to represent lower extremity-to-bumper impact, an upper legform for the thigh and pelvis-impact to the hood leading edge, and a child 2.5 kg and an adult 4.8 kg headform for the head-to-hood impact. The lower legform measures knee bending and shearing and upper tibia acceleration. The upper legform measures the contact force and bending moment and the headform measures linear acceleration in three directions at the headform's centre of gravity. The headforms are rotationally symmetrical thus not allowing rotational motion other than frictional. The ISO working group 2 developed specifications for a 3.5 kg child and a 4.5 kg adult headform (ISO, 2006, ISO, 2007). A new legform, FlexPLI (Flexible Pedestrian Legform Impactor), has been developed in Japan (Konosu and Tanahashi, 2003). In contrast to the WG17 legform it has a flexible tibia and femur measuring ligament elongation and tibia-bending moment, and has a knee design which allows new tests without part replacement. See Figure 6 for component test methods.

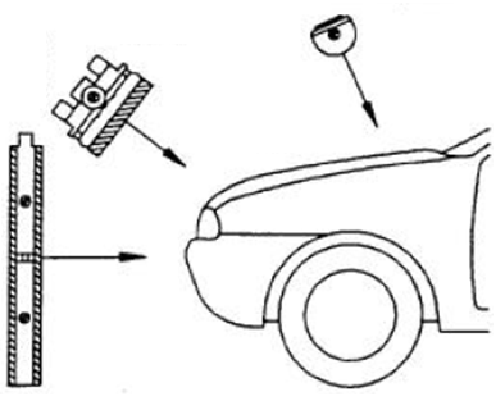


Figure 6. Component test methods

Several finite element head and brain models have been developed to estimate brain injury (Kleiven, 2006, Marjoux et al., 2008, Zhang et al., 2001). They are either used to study head impact to a numerical vehicle model, or can be used with kinematic output from experimental tests. In the latter alternative skull fractures cannot be studied. The skull is then considered rigid and the head motion from the experimental tests is induced to the skull of the model. These models have detailed representation of the head and brain in common. The Wayne State University (WSU) human head FE model for example features fine anatomical details of the head and brain and is made up of over 315 000 elements (Zhang et al., 2001). To reduce computation time and enable a tool to be used on regular personal computers, the SIMon model was developed by NHTSA (Takhounts et al., 2008). It is a less detailed finite element head and brain model which can estimate different types of brain injury. It has the potential to assess brain injury criteria in conjunction with regular crash tests.

Both full-body models and component test tools are valuable in evaluating the safety potential of countermeasures. The component test tools have good repeatability and can be used to study the detailed design of, for example, deployable hoods or airbags. Full-body models on the other hand are good tools for understanding the complex pedestrian impact (e.g. the interaction between shoulder and head impact), as well as the potential of countermeasures in more real-life conditions, for example the interaction of a deployable hood and windshield airbag as well as their interaction with auto-brake systems. Human body models can be used to study injury in greater detail. The component test tools for head testing can be further developed to include assessment of brain injury. The Polar dummy requires further study to develop injury criteria for the thorax, and human body models still need further development and validation.

2.4.2 Regulations and consumer tests

Regulations and consumer tests play a more important part in pedestrian protection than in occupant protection. Investing in a safe vehicle with regard to occupant protection is more in the interest of the car buyer. The striving of car manufacturers to perform well in car safety consumer tests has led to a rapid development of safety systems and improved safety for car occupants during the 2000s. For pedestrians, on the other hand, pedestrian regulations and consumer tests where the pedestrian rating is included in the overall rating of the car, is a necessity for the development of new safety systems and their introduction in production cars.

In 2005 the first legal requirements for pedestrian protection were introduced in both Europe and Japan. The EEVC WG 17 impactors and test methods were adopted by the European directive (EC, 2003). The lower legform is launched horizontally towards the vehicle bumper at 40 km/h (see Figure 6). Requirements were set for tibia acceleration as well as knee bending and shearing. For higher front-end vehicles, the upper legform is used in a vertical orientation to assess bumper performance, using requirements of force and bending moment. The upper legform for the front hood edge is used only for monitoring purposes where the impactor mass, impact angle and speed is dependent on vehicle geometry. The child and adult headform tests are performed at the front and rear sections of the hood area, respectively, determined by the wrap around distance (WAD) but limited to the hood area. The windshield area is excluded while for small vehicles the child area may include the entire hood area. EEVC WG17 (the report on which the directive is based) concluded, for the windshield area, that "*a considerable number of head injuries is caused by the windscreen or A-pillars…*" and "*proposes to perform further research in this field and not to include these areas already in the test methods*" (EEVC, 1998). Injury is assessed by the head injury criterion HIC_{15}. The headform impact speed in the directive was reduced to 35 km/h, which was argued to reflect a car impact speed of 40 km/h. The WG17 based its conclusions on AIS2+ injuries and, to a limited extent, AIS3+ injuries.

The Japanese directive includes the head-to-hood tests only, using the headforms developed by ISO. The impact angles are different from the European directive and depend additionally on vehicle geometry, divided into three vehicle categories. The headform impact speed is 32 km/h, lower than the European directive.

A second phase of the European directive was introduced in 2009 (EC, 2009). It was basically harmonized with global technical regulations (see following section). The two headforms, of 2.5 and 4.8 kg, were replaced by the ISO child headform of 3.5 kg. The injury criteria were raised to a slightly higher level. Further, a requirement of equipping the vehicle with a brake-assist system, to assist the driver to brake optimally, was introduced.

In 2009 a global technical regulation (GTR) to harmonize pedestrian protection was introduced (UN, 2009). It was almost identical to the second phase of the EC regulation, with legform-to-bumper and headform-to-hood tests based on a crash speed of 40 km/h, but did not require brake assist and included the possibility of raising the upper vehicle mass limit to 4.5 tons if so decided by the individual country. The EU regulation is limited to 2.5 tons. Further, the GTR plans to adopt the FlexPLI legform to replace the WG17 legform used by the EC regulation and as an intermediate solution in the GTR. In the early phase of the GTR development the intention was to include the windshield area, but this part of the test was removed due to feasibility issues. It was considered unfeasible to design a pedestrian-friendly windshield frame while meeting other vehicle stability requirements. Further, it was concluded that the glass impact caused a spread in the test results for identical windshields but that this was not yet fully understood (UN, 2009). In addition, the GTR includes a test method for deployable hood systems. Part of this test method uses numerical pedestrian models, a new method to assess pedestrian protection in a regulation. The GTR was based on AIS2+ pedestrian injuries.

In 1997 the European consumer organization Euro NCAP introduced pedestrian protection assessment of the most sold vehicles in Europe. They adopted the EEVC WG17 impactors and test methods, including the lower legform, upper legform and child and adult headforms. In contrast to legal tests they did not limit the headform tests to the hood area, but included the windshield area to a WAD of 2100 mm. They also retained the headform test speed of 40 km/h (Euro NCAP, 2011). The pedestrian rating of the car was initially excluded from the overall rating of the car. In 2009 Euro NCAP changed their assessment protocol to include pedestrian protection in the overall rating (Euro NCAP, 2009), which has led to a rapid development of the secondary (passive) protection of cars. They have also launched an “Advanced NCAP” assessment where primary safety systems such as autonomous braking systems for pedestrians are awarded.

The regulations and consumer pedestrian tests have been driving forces in the introduction of pedestrian safety measures, such as pedestrian bumpers and hoods in production cars. The question is whether these regulations and consumer tests are focusing on the right vehicle and body regions to effectively mitigate pedestrian injuries and fatalities. Furthermore, no regulation or consumer test considers injuries leading to permanent disability. These issues will be investigated in Study I and in a Preliminary study in this thesis.

2.4.3 Injury criteria

Knee bending and shearing and upper tibia acceleration are assessed as injury parameters in legal and consumer tests. The consumer tests have the strictest requirements with a maximum of 15 degrees bending, 6 mm shearing and 150 g acceleration, assessing knee ligament injury and tibia fracture. The upper legform force and bending moment is assessed as injury parameters in consumer tests to consider thigh and pelvic injury. Euro NCAP levels have been set at 5 kN and 300 Nm.

The head injury criterion, HIC_{15}, is used for head injury assessment in both pedestrian regulations and consumer tests. HIC is calculated from the head's centre-of-gravity resultant linear acceleration. It was shown by Prasad and Mertz (1985) that an impact of 15 ms or less was critical in skull fractures and concussions. The HIC is a measure of head injury severity which includes the effect of the head's linear acceleration and duration of acceleration. A higher acceleration can be tolerated for a short duration and vice versa for a longer duration. The duration assessed is maximized at 15 ms in pedestrian test applications.

An HIC of 1000 is assumed to equal the risk of a serious or more severe (AIS3+) head injury of 53% (NHTSA, 1995). Since the scale is not linear, a reduction of HIC to 500 reduces the risk to 13%. The HIC level of 1000 was chosen as a threshold level for both legal regulations and consumer tests, while an exemption zone has been allowed for a smaller part of the hood area in the European regulation. One third of the hood area is then allowed an HIC value of up to 1700 equaling a risk of 94% for AIS3+ head injury. As the HIC criterion is based on linear acceleration it is limited to assessing skull fractures and those brain injuries possibly caused by linear loading. There are several criteria proposed for brain injuries that take rotational loading into account. The cumulative strain damage measure (CSDM), relative motion damage measure (RMDM), and dilatational damage measure (DDM) are injury criteria for assessing the risk of diffuse axonal injuries (DAIs), acute subdural hematoma, and contusions/focal lesions respectively. Takhounts et al. (2008) concluded that CSDM and maximum principal strain correlated with brain injuries in animal tests. The CSDM measures the cumulative fraction of elements in the brain reaching a given strain level during an impact event.

While HIC is the dominating criterion, in countermeasure development, of assessing head injury and has proven a robust and successful tool to minimize head injury, it does not consider all types of head and brain injuries. Rotational loading is important when studying pedestrian head impact. CSDM is then a candidate, used in conjunction with numerical brain models. Study I-III will investigate these issues from different perspectives. Injury criteria for pedestrian chest impact, or assessment of the disability risk have not been considered.

2.5 COUNTERMEASURES

When the very first automobiles were introduced in the 1800s a law was passed in the UK stating that *"…self-propelled vehicles on public roads must be preceded by a man on foot waving a red flag and blowing a horn"*. The red flag law was not repealed until 1896. Hood ornaments were frequent in cars up to the 1950s but were voluntarily removed (or re-designed to yield) by car manufacturers. In the 1970s research on pedestrian protection in cars began to intensify. Hood systems with a greater deformation distance between the engine and hood were suggested to avoid pedestrian contact with the rigid under-hood components. The idea of a deployable hood to increase the energy absorption distance in the event of a crash was presented in 1978 (Volkswagen, 1978). Further, Appel (1977) showed a pedestrian protection airbag for the lower windshield as early as 1977. Aldman et al. (1985a) presented the idea of reducing the knee load by either lowering the bumper or introducing a second lower bumper impacting the tibia. The idea was to sacrifice the tibia arguing that a tibia fracture was easier to heal than a knee injury.

None or very few of these countermeasures were introduced in production cars. As discussed previously it was considered difficult to convince car customers to pay extra for safety for other than car occupants. It was not until 2005 with the introduction of pedestrian regulations that development gained momentum and increased even further in 2009 when Euro NCAP included the pedestrian test in the overall rating of the car. In the following sections more detail will be presented regarding recent secondary and primary safety systems.

2.5.1 Secondary (passive) safety systems

Secondary safety systems have been developed for the vehicle front, focusing on the bumper, hood edge, hood and windshield areas.

In recent years a rapid development in car bumper design has been seen. While the average car scored low in the legform-to-bumper test in 2004 most cars were rated "green" (full score) in Euro NCAP tests in 2009. The bumpers were redesigned with solutions such as thicker foam and an extra lower stiffener below the bumper to reduce loading of the knee which typically impacts at bumper height for an average adult. The lower stiffener impacts the tibia which, if fractured, is easier to heal than the knee. Airbag solutions have also been proposed to distribute and reduce the load on the lower extremities (Pipkorn et al., 2007) and headlights have been redesigned to be more energy absorbent (Lucas, 2000). Modern cars have a more aerodynamic design leading to a lower, less protruding, front hood edge with a lower risk of pelvis and thigh injuries. To mitigate thorax injuries to the hood edge in impacts to vehicles with higher front ends, such as sports utility vehicles (SUV), an airbag was proposed for the front hood edge (Fredriksson et al., 2007). The hood, wings and wiper engines have also been passively redesigned to improve energy absorption (Belingardi et al., 2009, Han and Lee, 2003).

Even if the hood surface design is optimized for energy absorption there may not be a sufficient deformation distance available to underlying parts in the engine compartment. It has been theoretically and experimentally proven that deformation distances of 60-70 mm can be sufficient to achieve HIC values below 1000 (Okamoto et al., 1994, Zellmer and Glaeser, 1994). A solution for this is to lift the hood in case of pedestrian impact. Active hoods, pop-up hoods or deployable hoods are different names for the concept of lifting the hood surface, usually by actuators in the rear corners of the hood (Fredriksson et al., 2001, Nagatomi et al., 2005, Oh et al., 2008). These systems are currently in production in vehicles from Jaguar, Citroën, Honda, BMW, Mercedes-Benz, Cadillac, Nissan and Porsche. They lift the rear hood part between 50 and 120 mm to enable energy absorption of the head impact preventing a second "bottoming out" impact to structures underneath the hood in the engine compartment. Fredriksson et al. (2009) showed, in a combined experimental and finite element study, that an under-hood distance of 100 mm reduced both skull fracture-related and brain-related injury criteria to acceptable levels in 40 km/h headform impacts. The same study with dummy tests using Polar II and a real vehicle showed a large reduction in head loading by a deployable hood system compared to a standard hood. For deployable hoods to be activated in accidents they are connected to a sensor and an actuator, which must make the decision and perform the lifting motion within a short time period. Dummy tests and simulations have shown that the deployed hood for a standard sedan-type passenger car must be in position within less than 60 ms after the first leg impact to the front of the car at a crash speed of 40 km/h. For the lower part of the windshield and the a-pillars, airbags have been proposed to enhance head protection (Autoliv, 2002, Autoliv, 2010, Crandall et al., 2002, Maki et al., 2003a). See Figure 7.

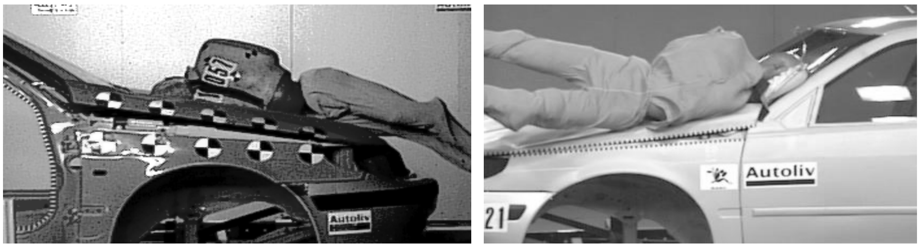


Figure 7. Deployable hood and windshield airbag (Fredriksson et al., 2002, Autoliv, 2001)

While mitigation of leg injuries is quite well known and implemented, only limited solutions to protect the upper body have been implemented thus far. The design solutions implemented for the head are limited to the hood area, where a minority of head injuries originates. No design solutions have been developed to mitigate chest injury. When introducing secondary safety countermeasures it is important to not only design them for legal and consumer component tests, but to also consider full-body loading. Study III addresses this issue.

2.5.2 Primary (active) safety systems

Primary safety systems have been introduced to either aid the driver in reducing speed or automatically reduce the speed of the impacting car in a pedestrian crash. The “brake assist” system in the brake pedal senses the braking intention of the driver and automatically optimizes braking performance. The brake assist systems were mandated in new vehicles in Europe in 2008. Infra-red systems detecting living creatures such as animals or pedestrians and displaying the image on a screen to the driver were introduced in the early 2000s (Cadillac, Lexus) and were later followed by systems which additionally warned the driver (BMW, Audi, Honda, Mercedes, Toyota). Since brake-assist systems are dependent on driver action they were estimated to be activated only in 50% of accidents (Hannawald and Kauer, 2004). It is then natural to develop this system into an automatic system without driver intervention. A system was introduced in 2009 that detected pedestrians and gently applied the brakes if no driver action was noticed after a warning (Lexus, 2011). Recently, an auto-brake system was introduced that detects pedestrians and automatically applies full braking before an imminent impact (VolvoCars, 2010). This system has been claimed to be able to brake to a full stop from 25 km/h and thereby completely avoid low-speed pedestrian crashes. At higher speeds, crash energy can be substantially reduced.

Figure 8. Primary pedestrian safety systems; (driver display of) pedestrian warning system (left), auto-brake system detecting pedestrians at danger (right)

The pre-crash, or primary, safety measures and the in-crash, or secondary, safety measures can be combined into integrated systems. Integrated pedestrian systems have not been introduced in production cars. It is unclear whether an integrated system would be more effective than a single primary system such as autonomous braking. When developing an integrated system it is also important to study how the two parts of the system interact. This can be performed using full-body impacts, and introducing both primary and secondary countermeasures. This is investigated in Study III.

2.5.3 Effectiveness / Potential of countermeasures

Studies have tried to estimate the effectiveness of pedestrian protection systems. Lawrence et al. (2006) estimated the effectiveness of reducing fatally and seriously injured pedestrians, by introducing brake assist systems, to 10%. If the vehicle could brake autonomously the effectiveness of the system would be increased. Rosén et al. (2010) estimated that an auto-brake system, activated for all visible pedestrians within a forward-looking angle of 40 degrees one second prior to impact, would reduce fatalities (when struck by car fronts) by 40% and seriously injured by 27%.

It is unclear whether primary safety measures, such as automatic braking, can be enhanced by secondary safety measures. Fredriksson and Rosén (2010) studied 54 representative, severely head injured (AIS3+) pedestrians in detail to estimate the potential of theoretical primary and secondary systems and the potential of combining them into an integrated system. The primary safety system was assumed to brake (up to 0.6 g, depending on road friction) for all visible pedestrians one second prior to crash. The secondary system consisted of a deployable hood system and a lower windshield/A-pillar airbag covering up to 2.1 m WAD, estimated to be fully effective (when impacted) in avoiding AIS3+ injury up to 40 km/h and then have a linearly decreasing effectiveness. The study concluded that the passive (secondary) system could protect 34% of the severely head injured (AIS3+) and the active (primary) system 44%. If combining the systems into an integrated system it protected a significantly higher number, 64% of the pedestrians, from severe (AIS3+) head injury. See Figure 9.

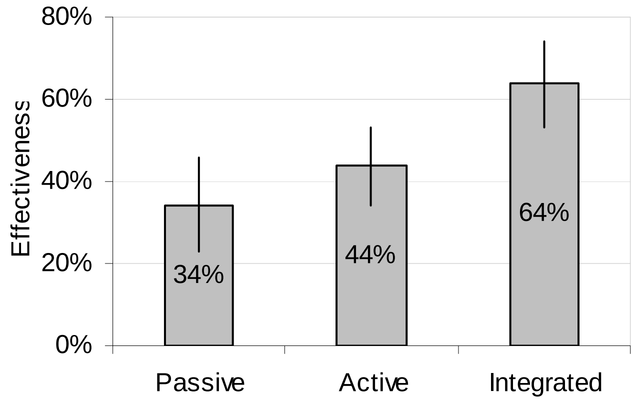


Figure 9. Effectiveness of passive (secondary), active (primary) and integrated systems (Fredriksson and Rosén, 2010)

Although the Fredriksson and Rosén study showed theoretically that primary and secondary systems complement each other to increase the protection potential, there is a need to further study the potential of integrated systems including information from real tests or simulations with the countermeasures.

2.6 SUMMARY OF BACKGROUND

In a typical (western world) car-to-pedestrian accident, a walking pedestrian is impacted on the side by a passenger car front. The car bumper typically impacts the leg first, followed by a thigh or pelvis impact to the hood edge and the upper body wrapping around the hood edge with a subsequent thorax and head impact to the hood and windshield areas. Naturally, head impact location is dependent on pedestrian height but has also proven to be influenced by impact speed and pedestrian height relative to car front height, leading to different amounts of upper body sliding on the hood surface. Older pedestrians are overrepresented in more severe accidents, while gender does not influence the risk. Impact speed is highly influential on the injury outcome, since a relatively small change in impact speed changes the risk dramatically.

Although legal regulations concentrate on head protection from the hood area, several studies suggest that other areas, such as the windshield area, may produce more injuries in adults while children receive a majority of head injuries from the hood area. The existing head injury criterion considers linear loading only. Several studies have shown the need for head assessment criteria taking rotational loading into account. Chest injuries have been shown to be frequent, a body region not considered in any requirement. Long-term disabling injuries have also been shown to be frequent for pedestrians but need further study. To conclude, this indicates that countermeasures for the windshield area are necessary, and that both hood- and windshield-located countermeasures should take chest loading and head rotational loading into account.

Component test tools have been developed for leg-to-bumper impact, pelvis-to-hood edge impact and head-to-hood impact. With their high repeatability and the possibility of testing any impact point they are suitable tools for regulation and consumer testing. To provide better understanding of the complex vehicle-to-pedestrian impact, dummies and full-body models have been developed. They can be used for example to study the interaction between chest impact and subsequent head impact, and if countermeasures work as intended. Detailed head and brain numerical models have been developed to evaluate brain injury.

Regulations and consumer tests have been introduced and have recently led to a rapid development and introduction of pedestrian countermeasures. Primary systems to aid the driver in braking, such as brake-assist, night-vision and auto-brake systems, have also been introduced to enhance pedestrian safety. The focus of secondary (in-crash) pedestrian protection systems to date has been on leg protection in bumper impact and head protection in hood impact. Many new cars have improved leg protection capability of the bumper and some improvements have also been made to the hood area. For both the bumper and hood areas passive solutions with increased deformation distance have been introduced. A few car models have also introduced deployable hood systems to increase the deformation distance when needed in a crash. While leg protection has been implemented on a broad basis in production cars in a car location from which most leg injuries originate, the upper body countermeasures implemented thus far have been limited to address head injuries only and in an area from where a minority of these injuries originate.

There is a need to study severe accidents in more detail to understand the most frequent upper body disabling and fatal injuries and their car sources, to prioritize secondary countermeasure design and location addressing most injuries and then to estimate the potential of secondary countermeasures compared to primary and integrated countermeasures.

3 AIMS

The general objective of this thesis was to determine priorities for and evaluate the potential of car-based countermeasures designed to mitigate severe upper-body injuries and fatalities sustained by pedestrians in impacts by cars. Furthermore, injuries leading to medical impairment were considered.

Thus, the general objective was divided into the following aims:

- To use in-depth, real-world accident data to uncover the most frequent combinations of severely injured body regions and their car sources and at what impact speeds they occur most frequently. (Study I)
- To evaluate the influence of pedestrian head impact speed and under-hood distance on head and brain loading, using a component-based experimental and computational approach. (Study II)
- To study the potential of primary (auto-brake), secondary (deployable hood and airbag), and integrated countermeasures respectively, to reduce pedestrian head and chest loading in full-scale simulations using an advanced pedestrian numerical dummy and generic vehicle models. (Study III)
- To determine the most common body regions of pedestrians sustaining fatal injury and their car impact locations by studying fatal crashes. (Preliminary study)

4 SUMMARY OF PAPERS

4.1 STUDY I: PRIORITIES OF PEDESTRIAN PROTECTION – A REAL-LIFE STUDY OF SEVERE INJURIES AND CAR SOURCES

4.1.1 Method and Materials

The in-depth German database GIDAS was queried for pedestrians struck by the front of passenger cars or vans. This database collects cases from all traffic accidents where at least one person has been injured (AIS1+) in defined areas around Dresden and Hannover chosen to be representative of Germany. Cases were included from 1999 to 2008 which resulted in 1030 cases of which the 161 severely injured (AIS3+) were included in this study.

Injuries were divided into five body regions; head (including head and face), neck, chest (including thorax, abdomen and spine), arms (upper extremities) and legs (lower extremities including pelvis). Empirical distributions of impact speeds were derived for body regions with sufficient numbers of AIS3+ injuries (head, chest and leg) and gamma distributions were used to fit the empirical distributions of impact speed. Risk functions for AIS3+ injuries to the head, chest and legs were derived by weighted logistic regression. In the risk estimation weighting was used according to Rosén and Sander (2009). Long term injury outcome was estimated using risk matrices, based on AIS injury level and body region, developed by Malm et al. (2008). This was conducted for the levels of 1% and 10% permanent medical impairment. Injury sources were studied in detail for each case using post-crash pictures. For each AIS3+ injured body region the impact source was located in a standardized vehicle front graph.

4.1.2 Results

Of the 161 severely (AIS3+) injured pedestrians, 58% sustained severe injuries to the legs, 43% to the head, and 37% to the chest. Head and leg injury seemed to be equally frequent for different ages, while the chest seemed to be less frequently injured in the children (0-14) and more frequently injured in the seniors (65+) (see Figure 10).

Of all surviving pedestrians 31% were estimated to sustain at least 1% impairment (the lowest level of impairment), while 5% sustained the more severe impairment level of at least 10% impairment. The leg was estimated as the most frequently impaired body region for the lower impairment level (1% or more), followed by arm and head. For the more severe impairments (10% or more), the head was the dominating body region.

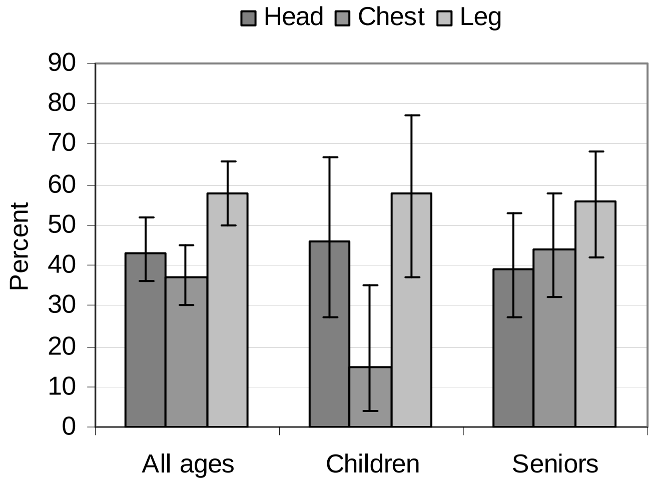


Figure 10. Body region AIS3+ injury distribution by age groups (95% confidence intervals)

The most frequent injury/source combinations were leg-to-front end (sustained by 44% of the pedestrians, CI 36-52%) and head-to-windshield area (26%, CI 19-33%). Chest-to-hood area occurred in 15% (10-21%) and chest to windshield area in 13% (CI 8-19%) of the cases. Typical impact speeds (corresponding to the maximum of the incidence curve), also called modal value, were 45 km/h for head-to-windshield and 50-55 km/h for chest impacts to the hood and windshield areas (see Figure 11 and Figure 12). The risk of sustaining a severe injury at a car impact speed of 50 km/h was 13% (CI 9-18%) for the head and 11% (CI 8-15%) for the chest.

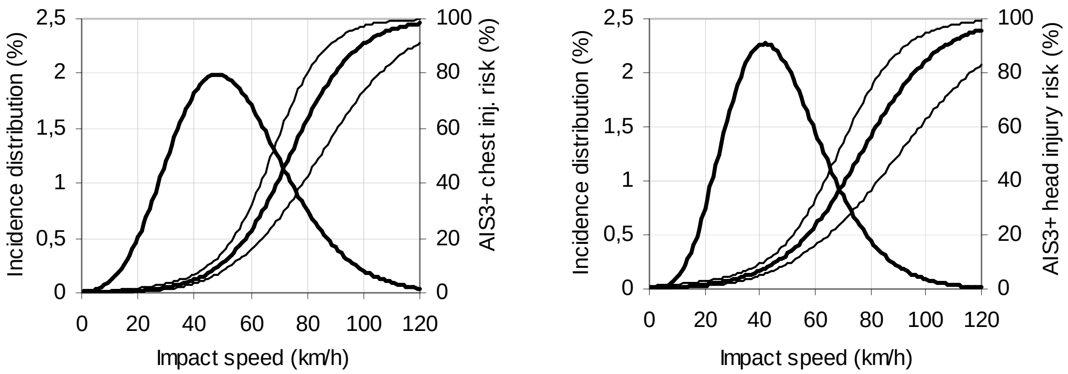


Figure 11. AIS3+ incidence and risk (95% CI) as functions of car impact speed for chest (left) and head (right)

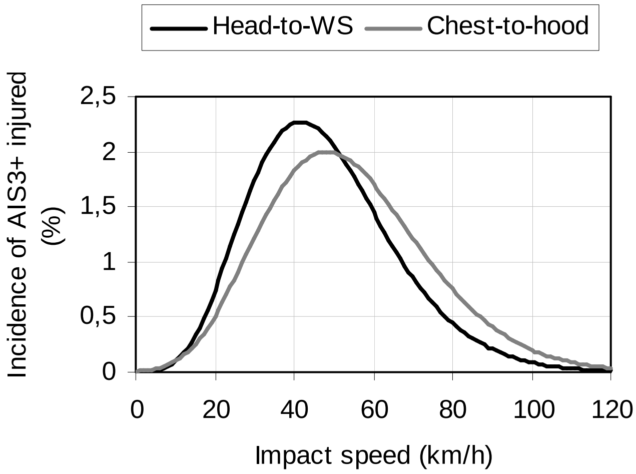


Figure 12. Impact speed distributions for most common injury/source combinations (head-to-windshield and chest-to-hood)

A majority of the head injuries from the windshield area were caused by the structural area (72%, CI 55-85%). Accordingly, a minority was caused by the remaining glass area. Sixty percent (CI, 42-76%) of the pedestrian head impacts were within a wrap around distance (WAD) of 2100 mm (2.1 m) and 86% (CI, 70-95%) within a WAD of 2300 mm.

4.2 STUDY II: INFLUENCE OF IMPACT SPEED ON HEAD AND BRAIN INJURY OUTCOME IN VULNERABLE ROAD USER IMPACTS TO THE CAR HOOD

4.2.1 Method and Materials

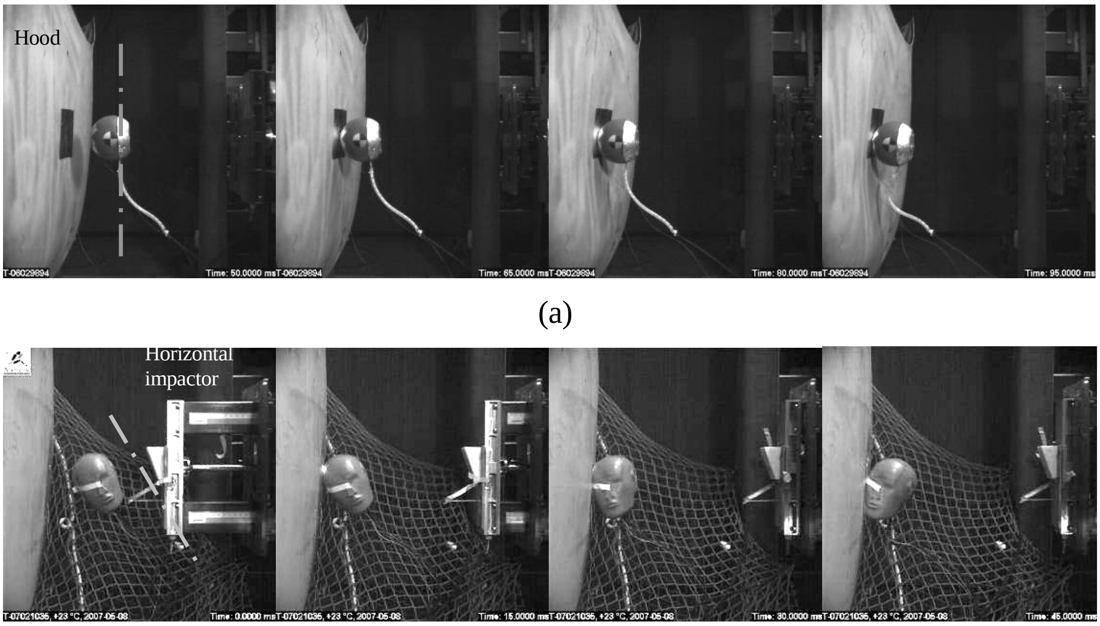
The study consisted of two parts. The first part was experimental headform component tests to a car hood. The output from the experimental tests was used as input in numerical simulations with a detailed finite element brain model.

4.2.1.1 Experimental tests

The headform tests were performed with two different headforms. The EEVC WG17 adult headform was used to study linear loading of the head, and the Hybrid III 50th percentile adult head was used to study induced rotational loading (Figure 13). The pedestrian headform is rotationally symmetric with a circular shape which leads to the normal force always acting through the head's center of gravity. The Hybrid III head has a human-like head shape which enables impacts with the normal force offset to the center of gravity which then induces rotation. The Hybrid III head was equipped with a 12-accelerometer array to measure translational and rotational acceleration in six axes.

Both headforms were launched free-flying against the hood at varying impact speeds and under-hood distances. The Hybrid III head was pre-set at an angle of 30 degrees around the X (fore-aft longitudinal) axis, found in an earlier study to maximize rotation of the head (Fredriksson et al., 2009), so that the top side of the head contacted the hood surface first (Figure 13).

0 ms **15 ms** **30 ms** **45 ms**



(b)

Figure 13. Test setup in: a) pedestrian headform tests, b) Hybrid III headform tests with induced rotation (note: hood in vertical position)

4.2.1.2 Brain simulations

The Wayne State University Head Injury Model (WSUHIM) (Zhang et al., 2001) was used to assess brain loading in the rotational tests. It is a detailed head and brain injury model consisting of over 315 000 elements with fine anatomical details (see Figure 14). The experimental kinematic output (six axes linear and rotational acceleration) was used as input to the WSUHIM model. Brain loading was assessed using the cumulative strain damage measure (CSDM). CSDM is a measure that monitors the accumulated volume of the brain (in %) that exceeds a given strain level, in this study 0.35 for mild traumatic brain injury (TBI) and 0.5 strain for moderate to severe TBI.

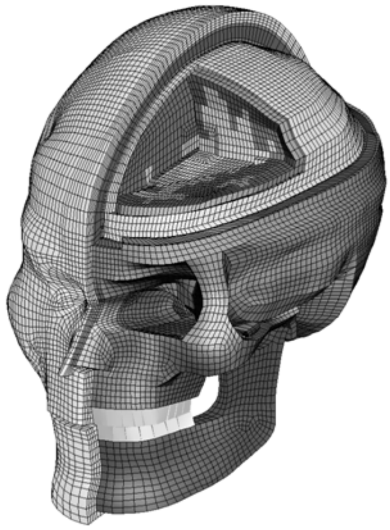


Figure 14. Wayne State University Head Injury Model

4.2.2 Results

Under-hood distances of 60, 80 and 100 mm in 20, 30 and 40 km/h head impact speed respectively, resulted in HIC values below 800 and an affected brain volume of less than or around 2% for 0.35 strain. See Figure 15. A 20 mm increase in under-hood distance was comparable to a 10 km/h impact speed reduction regarding the influence on head and brain impact loading, and if those measures were combined the head and brain loading was further reduced.

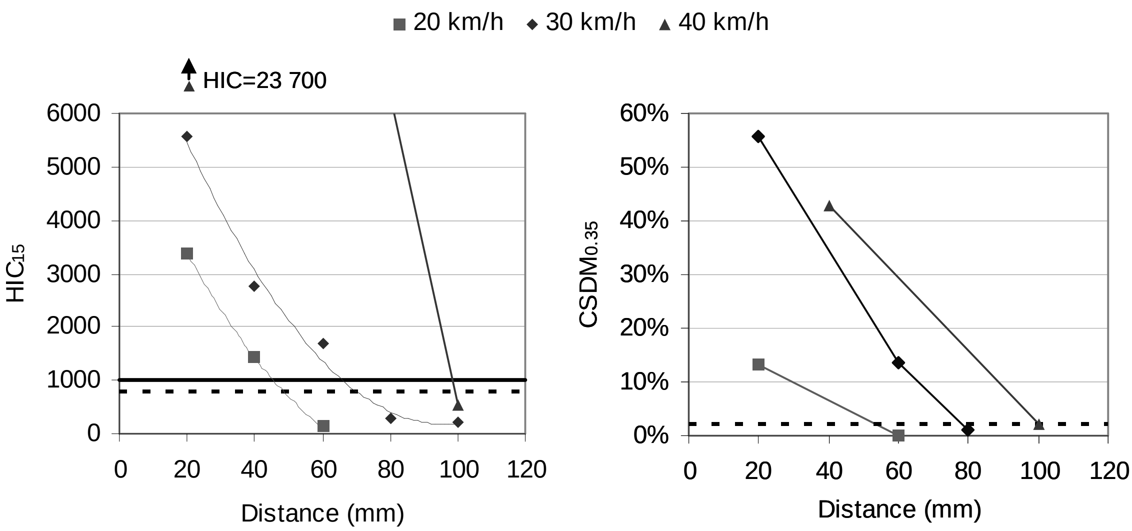


Figure 15. HIC_{15} and $CSDM_{0.35}$ influence of under-hood distance and impact speed

4.3 STUDY III: POTENTIAL OF PEDESTRIAN PROTECTION SYSTEMS – A PARAMETER STUDY USING FINITE ELEMENT MODELS OF PEDESTRIAN DUMMY AND GENERIC PASSENGER VEHICLES

4.3.1 Method and Materials

This study used full-body finite element simulations with the Polar II pedestrian dummy model and generic sedan-type vehicle fronts to study the influence of pedestrian countermeasures on head and chest loading. The countermeasures chosen were (1), a primary (auto-brake) system, (2) a secondary deployable system and (3), an integrated system. The automatic braking was modeled by a 10 km/h pre-impact speed reduction (equal to full braking in 0.3 s) and a vehicle pitch of 1 degree and in-crash deceleration of 1 g. The deployable system consisted of a deployable hood, lifting 100 mm in the rear, and a lower windshield airbag. The integrated system combined the primary and secondary system.

Three impact configurations were chosen using conclusions about most common configurations from Study I; namely 1) head-to-windshield and chest-to-hood (“Mid”), 2) head/chest-to-windshield (“High”) and 3) head/chest-to-hood (“Low”). To find the right impact configurations different vehicle sizes and dummy sizes were combined. This resulted in two different vehicle sizes, a mid-size and a large sedan, and the two sizes of 50th and 95th percentile male dummy being used. All three configurations were performed at a 40 km/h pre-impact speed, and the two higher (and most common) impact configurations were repeated at a 50 km/h impact speed (see Figure 16). These five configurations were performed for the reference vehicles and vehicles equipped with the three different countermeasures resulting in a total of 20 simulations.

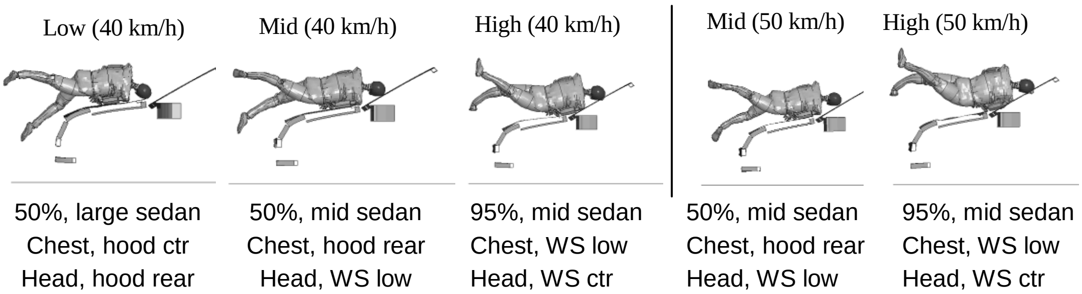


Figure 16. Impact configurations in the reference simulations

Chest contact force, head injury criterion (HIC_{15}), head angular acceleration, and the cumulative strain damage measure ($CSDM_{0.25}$) were employed as injury parameters. CSDM was assessed with the SIMon brain model using head acceleration data from the full-body simulations as input.

The head impact location may be influenced by braking due to two different parameters; the speed change and the vehicle pitch/deceleration during crash causing a lower front. The study setup allowed comparison of the influence of these parameters separately.

4.3.2 Results

In the ten simulations without deployable countermeasures, head impact time ranged from approximately 170-185 ms in 30 km/h, 125-145 ms in 40 km/h impact and 110-120 ms in 50 km/h. The larger dummy (95^{th} percentile male) had a 10-20 ms later head impact time compared to the 50^{th} percentile male. Wrap around distance (WAD) to head impact ranged from 180-213 cm (dummy statures 175 and 187 cm, (Untaroiu et al., 2008)) for the 40 km/h impacts, and increased with increased impact speed and was influenced by car type as well.

Head impact velocities were in all cases lower than the car impact speed, ranging between 73% and 93% calculated as the head/car velocity ratio. The lowest velocity ratio was found for the configuration of the head hitting the hood ("low" configuration).When the car impact speed was changed, the head impact speed changed less. When decreasing impact speed from 50 to 40 km/h (with otherwise identical impact configuration), the head impact speed was decreased by 2.9-4.7 km/h. When reducing car impact speed from 40 to 30 km/h, the head impact speed was reduced by 5.8-8.7 km/h.

The head-to-windshield-center ("high") impacts resulted in low head loading. The highest head loading was recorded for head impacts to the rear hood and lower windshield ("low" and "mid"). The highest chest force was recorded when the chest impacted the lower windshield and instrument panel ("high").

The typical influence of the countermeasures can be seen for one configuration in Figure 17 where the head linear acceleration is shown. The passive countermeasure reduced peak acceleration but otherwise displayed a similar curve shape. The braking system delayed the peak and decreased all values of the event. The integrated system had the same delayed trend as the braking system and reduced the peak value further.

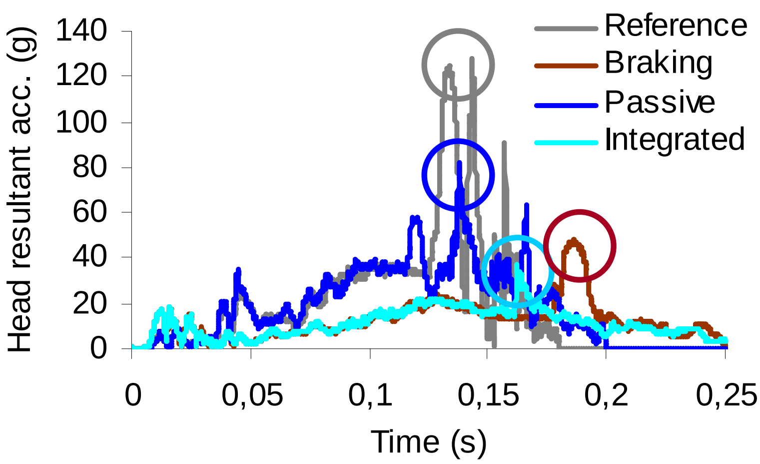


Figure 17. Example of head resultant linear acceleration for one impact configuration (low impact at medium speed)

All three countermeasures showed benefit in a majority of impact configurations in terms of injury prevention (Figure 18). The auto-brake system reduced chest force in a majority of the configurations and decreased HIC15, head angular acceleration, and CSDM in all configurations. Averaging all five impact configurations, the auto-braking showed reductions of injury predictors between 20% (chest force) and 82% (HIC) relative to the reference situation. The passive countermeasure reduced chest force and HIC_{15} in a majority of configurations and head angular acceleration and CSDM in all configurations, although the CSDM decrease in two configurations was minimal. Average reductions between 20% (CSDM) and 58% (HIC) were recorded for the passive deployable countermeasures. Finally, the integrated system reduced all injury assessment parameters in all configurations compared to the reference situations. The average reductions achieved by the integrated system ranged between 56% (CSDM) and 85% (HIC).

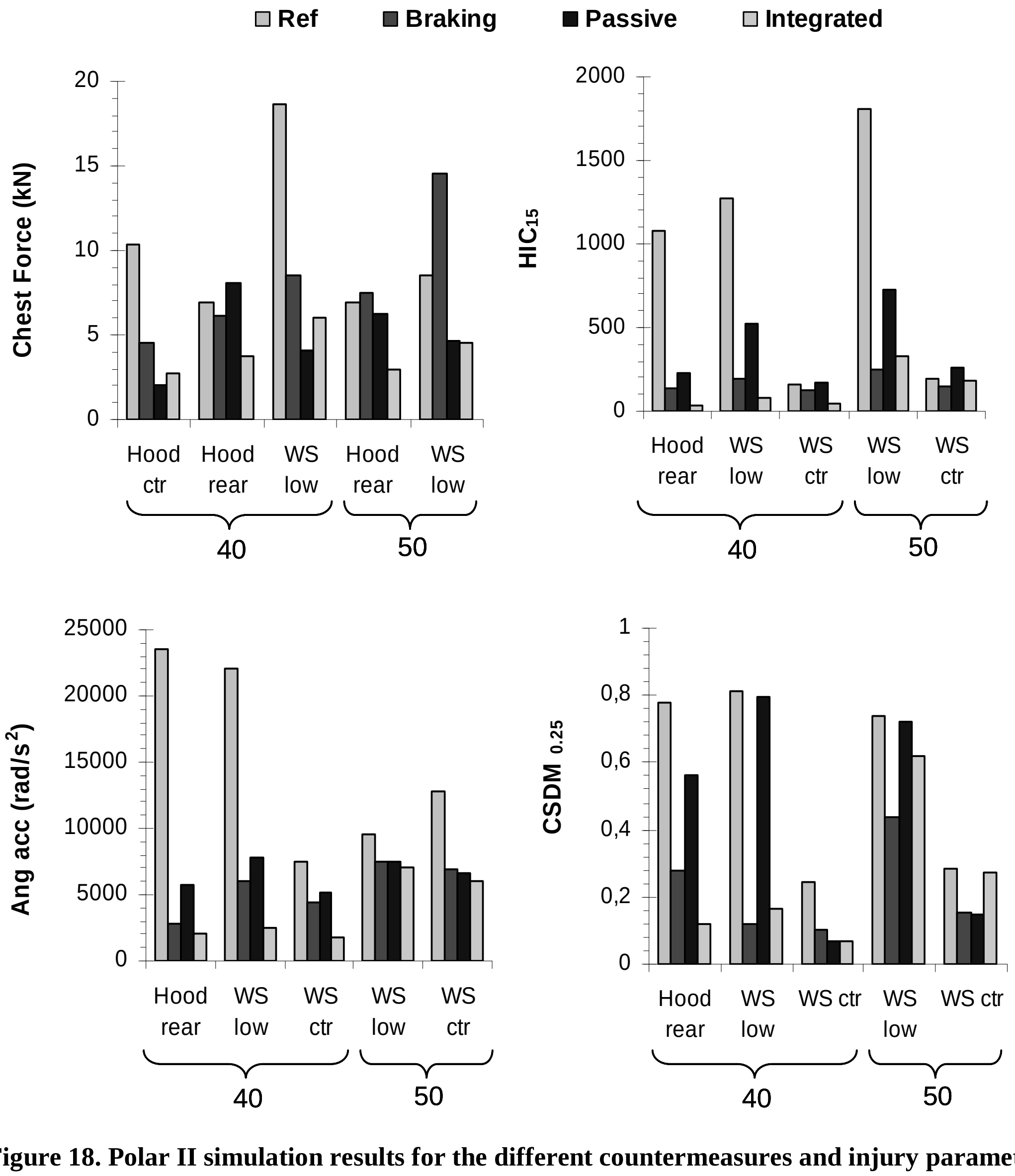


Figure 18. Polar II simulation results for the different countermeasures and injury parameters (pre-impact traveling speed (km/h) given)

On average the head impact wrap around distance was decreased 110 mm for the auto-brake cases compared to the same reference cases. Decreasing the impact speed alone by 10 km/h, without change of pitch/in-crash deceleration, decreased the wrap around distance by an average of 100 mm. The pitch/deceleration change alone changed the WAD less than ±30 mm, but although the WAD was not changed significantly the head impacted different structures due to the lower vehicle front in the pitch condition. The head therefore impacted 20-80 mm more rearward relative to car structures in the pitch cases.

4.4 PRELIMINARY STUDY: FATAL CAR-TO-PEDESTRIAN CRASHES IN SWEDEN - CAUSES AND INJURY SOURCES

These preliminary results are based on a study performed by Öman, Fredriksson, Bylund and Björnstig (2011), planned to be published later.

4.4.1 Introduction and Aim

Longhitano et al. (2005) and Study I had concluded the most frequent combinations of injuries and their car sources in pedestrian crashes using representative data sets. The studies were based on moderate to severe injuries. No study was found that analyzed in-depth a representative data set of fatal crashes to determine the distribution of injury/source combinations in car-to-pedestrian crashes. The aim was to study fatal car-to-pedestrian crashes in Sweden to determine the most common body regions of pedestrians sustaining fatal injury and their car impact sources.

4.4.2 Method and Materials

Since 1997 investigators from the seven regions of the Swedish Transport Administration (STA) analyze all fatal traffic crashes in Sweden, collecting on-site comprehensive information of road and surrounding conditions, detailed vehicle data including photo documentation and all available medical and forensic records from the casualty. Fatal injury is defined as mortality within 30 days due to crash-related injuries. The information is gathered in a central database which includes all fatal road accidents in Sweden.

The STA central database was used in this study to extract all pedestrian accidents between November 2004 and December 2007 that met the following inclusion criteria: pedestrians of all ages impacted by the front of passenger vehicles (such as cars, sports utility vehicles (SUV), and multi-purpose vehicles (MPV)). Cases were excluded when additional non-standard equipment (i.e. bull-bars) was mounted to the front, and if sufficient information to perform an impact source analysis of the vehicle was not available. This resulted in 58 accidents.

A medical analysis of the information in the database was performed by two medical professionals to determine the body region, or regions, containing the injury causing death in each case. The car part responsible for causing fatal injury was also determined by the authors in each case. The car front was, in this analysis, divided into bumper, hood front edge, hood area and windscreen area. While the other parts have rather uniform properties, the windshield area consists of parts with significantly different properties. Therefore a more detailed analysis was performed of the impact points for the windshield area (Figure 19). The windshield area was further divided, where the structural area of the windshield was defined as the frame area, the near-frame area and the instrument panel area with the remaining area constituting the pure glass area (Figure 20). Finally, the impact points were positioned relatively in horizontal and vertical directions in a standardized windshield graph, similar to methods from previous studies (Fredriksson et al, 2010, Koetje and Grabowski, 2008).

Figure 19. Five examples from detailed impact location analysis

4.4.3 Results

In the 58 accidents the posted speed limit of the accident scene was ≥70 km/h in 48% of the crashes, and braking was applied in 19% of the 54 crashes with a known braking status. Fifty-one victims were impacted by a passenger car, 5 by an MPV and 2 by an SUV. The median model year of the vehicles was 1997. Children < 15 years of age were victims in 6% of fatal crashes, while seniors ≥ 65 accounted for 43% of the crashes. The mean age of the pedestrians was 53 years, and 53% were male. The pedestrians were impacted from the side in 64% of the cases.

The primary cause of death was head and neck injury in 66%, thorax in 23%, and abdomen and pelvis in 9% of cases. The most common combinations for cause of death and car impact location were head and neck injury from the windshield area at 53%, thorax-to-windshield area 13%, thorax-to-hood 8%, head-to-hood 5% and abdomen and pelvis-to hood leading edge, 5%. In five cases, injuries to more than one body region were estimated to cause death. When studying fatal injury and age of pedestrians, all ≤ 15 years of age (n=6) had brain injury as the sole cause of death, while 34% of adults (16-64, n=27) and 55% of seniors (≥ 65, n=25) had other fatal causes, predominantly thorax injuries.

A standardized windshield graph was created where the exact location of fatal windshield impacts could be visualized (see Figure 20). In five cases pictures of sufficient quality were missing. The detailed analysis therefore consisted of 37 fatal impacts from 36 pedestrians. The windshield structural area caused 88% of the fatal head and neck injuries, 65% were attributable to the frame or near frame and 23% to the instrument panel area. Thorax injuries in the windshield area were also concentrated to the structural area, with all injuries originating from the frame area (A-pillars and roof edge). In the hood area, injuries were more evenly distributed, with a higher proportion on the driver's right side of the car. All pelvic injuries were caused by the hood's leading edge.

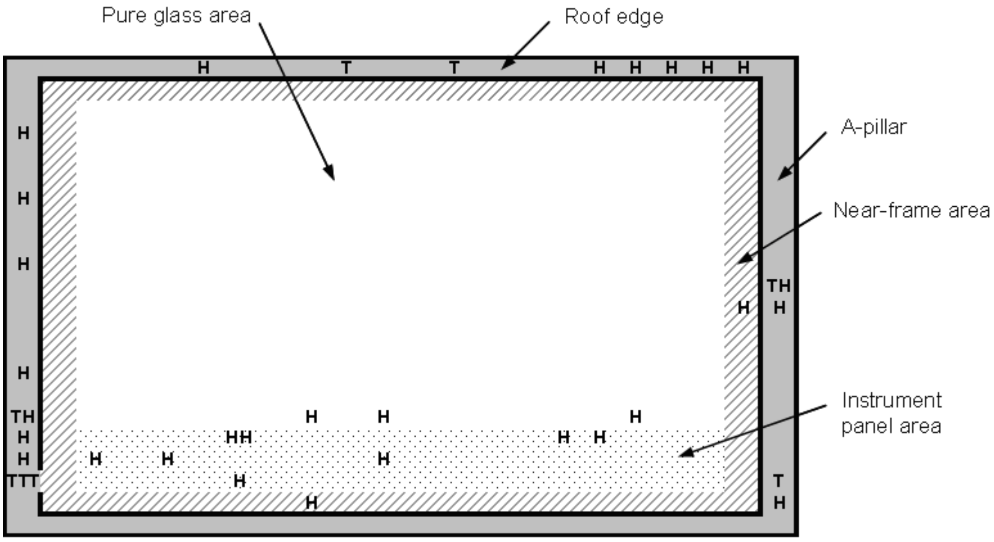


Figure 20. Standardized windshield and fatal cause impact locations (H=Head and neck, T=Thorax)

Eight of the 58 fatalities sustained head and neck or thorax injuries from the roof edge. These cases were studied in detail regarding car size, pedestrian size and posted speed limit. None of these parameters were found to be significantly different compared to the other fatal cases. Three pedestrians received their fatal head and neck injuries from the hood area. All three victims were short (121, 150 and 166 cm), the shortest being a 7-year-old child. All three cars were medium to large sedan-type cars, and the tallest victim was impacted by a large car.

4.4.4 Discussion and Limitations

This study showed, in agreement with Study I, that head-to-windshield was the dominating upper-body injury/source combination and that the detailed windshield impact locations causing injury were concentrated to the structural parts, but for the fatal cases the concentration to the structural area was even higher. Finally this study, as did Study I, concluded that chest injury was frequent from both hood and windshield areas.

The study is limited to one country, Sweden, a country with rather large cars in general. The results of this study showed a large proportion of injuries from the windshield. It is possible that this proportion could be even higher in other countries if the cars in this study are larger than average cars in other countries.

The study was limited to three years of fatal crashes resulting in 58 accidents. When more accidents are available in the future, the influence of car size or car type on fatal injury outcome could be studied.

4.4.5 Conclusions

The most common injury/source combination in fatal accidents was head-to-windshield area, followed by thorax injury from the hood and windshield areas. Head injuries from the hood area were sustained typically by shorter people or children. Children in all cases had only a head injury as the fatal cause, while older people more often also sustained thorax injuries. The dominant proportion of injuries from the windshield area was caused by structural parts.

5 GENERAL DISCUSSION

Pedestrian traffic injuries and fatalities is a large problem globally, where vehicle-to-pedestrian crashes are estimated to result in 400 000 deaths yearly (Naci et al., 2009). Large numbers are also estimated to sustain long-term disabling injuries.

It is known that leg and head injuries are frequent in pedestrian crashes, and legal and consumer tests have been developed to mitigate these injuries. Legal tests have concentrated on the bumper and hood areas, and countermeasures have been developed for these areas. Test results have shown promising results for bumper countermeasures in current cars, while the same improvements have not been shown for the hood area. Accident studies already showed at the start of this project that the windshield area was an important area (Longhitano et al., 2005, Okamoto et al., 2003, Yao et al., 2008), but no measures had been introduced at the time to mitigate injuries from this area. Different head impact airbags for the windshield area had been presented but were neither evaluated nor implemented. Chest injuries were considered in limited research studies, but mainly for sports utility vehicles, and had not been considered in injury mitigation technologies.

Limited research had been performed on primary pedestrian safety systems at the start of this project. Brake-assist systems were available to aid the driver in optimizing braking. Night-vision systems had been developed which enhanced the ability of the driver to detect pedestrians, especially in poor visibility conditions. Integrated systems of primary and secondary pedestrian safety had not been considered.

This thesis investigated what priorities should be set on secondary (in-crash) countermeasures for the upper body regarding coverage area and test speeds. Further, the thesis investigated the potential of secondary countermeasures, as well as if and how primary countermeasures, such as autonomous braking, could improve the potential of secondary countermeasures mitigating pedestrian injuries and fatalities.

5.1 THE ACCIDENT

5.1.1 Non-vehicle related factors

In a typical car-to-pedestrian crash the car front hits the pedestrian in the side in a walking position. Basically all pedestrian kinematic studies have used the lateral impact configuration in a walking stance. Both the PMHS tests referenced in the background section and Study III in this thesis base the conclusions on this impact configuration, which may limit our conclusions for other impact directions. However, in the accident cases in this thesis the impact to the pedestrian was lateral for 64% to 86% of the pedestrians which is in accordance with other studies (Okamoto et al., 2003, Yao et al., 2007, Yao et al., 2008).

The mean age of the study group (AIS3+) in Study I was 49 years, while the subset in Study I with fatal outcomes had a mean age of 57 years. In the Preliminary study of fatal crashes the pedestrians had a mean age of 53 years. In Study I it was possible to compare with the larger sample from which the study group was selected and the mean age of AIS2+ injured was 42 years and for all injured (AIS1+) 36 years. A comparison of the age distributions in accidents with different severities in this thesis is presented in Figure 21, where it can be seen that the proportion of elderly increases with the severity of the injury outcome. These results are in line with results from Rosén and Sander (2009) and Henary et al. (2006).

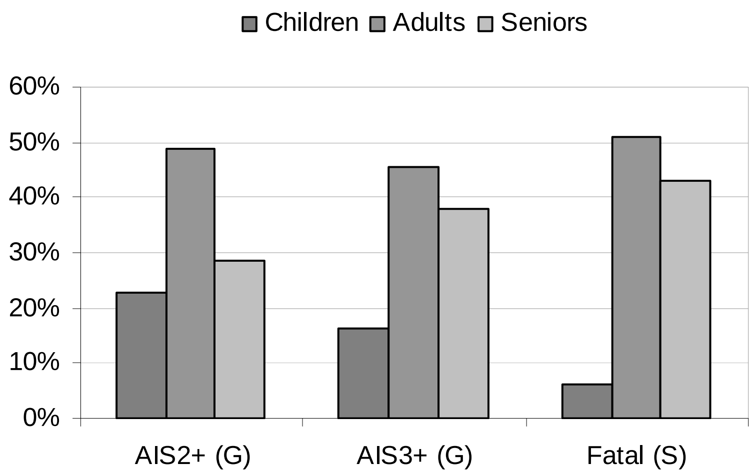


Figure 21. Age distribution of AIS2+, AIS3+ (Germany) and fatal (Sweden) pedestrian accidents (children 0-14 years old, adults 15-64 years old, and seniors 65+ years old)

5.1.2 Vehicle-related factors

The Preliminary study of fatal crashes in this thesis showed that half the fatal crashes occurred at posted speed limits of ≥70 km/h. The influence of impact speed on risk was concluded in Study I where risk functions could be derived for the three most injured body regions. In all cases the risk decreased significantly with lower impact speed. Reducing the impact speed by 10 km/h from 50 to 40 km/h or 40 to 30 km/h reduced the risk of severe injury for the head, chest or leg respectively by approximately 50%. If reducing the impact speed by 20 km/h from 50 to 30 km/h the risks were decreased 70 to 80% for the three most injured body regions. Rosén and Sander (2009) showed similar figures for fatal injuries.

Braking was not applied in a large majority of the fatal accidents in the Preliminary study. Hannawald and Kauer (2004) showed that half of pedestrian accidents do not involve braking or only a low level of braking. This indicates that not only do the fatal accidents occur in areas with high traveling speed, but a reduction of speed before crash also occurs infrequently. This shows that brake-assist systems would have limited effectiveness in these fatal crashes since these systems need braking action from the driver. Autonomous braking systems, on the other hand, would have both a high potential to reduce impact speed in a majority of these cases, as well as a high potential to reduce injury risk in the cases where they are activated. If sensor detection can be developed to a high detection rate these systems have a great potential to reduce disability and fatality rates.

5.1.3 Injuries and injury sources

This thesis found, in accordance with other studies, that the most frequently injured body regions, in car-to-pedestrian crashes, were the lower extremities and the head. Leg injuries were predominantly less severe and of a moderate to serious injury level, while head injury was the most frequent cause of fatal injury (Longhitano et al., 2005, Maki et al., 2003b, Roudsari et al., 2005, Zhang et al., 2008). However, this thesis also found that chest injury was a frequent cause of severe and fatal injury to adults. Elderly people had a higher and children a lower rate of chest injuries compared to middle-aged adults, while the rate of head injury seemed more equally distributed between age groups. Similar findings have been reported for elderly car occupants exposed to crashes (Kent, 2009).

In Study I it was concluded that for severe chest and head injuries both skeletal and soft tissue injuries were common. The head injuries in the windshield area were further studied using a method by Martin and Eppinger (2002) which links the full AIS codes to linear or rotational types of head injury. For the injuries where the direction could be determined, about 50% were linked to a combined linear and rotational loading while roughly 40% of the injuries were linked to pure linear loading. Similar findings have been reported by Arregui-Dalmases (2006) for pedestrian head injuries in general. This implies that rotational loading and brain injury should be considered when assessing head injury.

Even those severely injured can in many cases be treated without sustaining disability, while others sustain disabling injuries for less severe injuries. Study I estimated that as many as 31% of the surviving pedestrians (AIS1+) would receive a permanently impairing injury at the 1% level and 5% would sustain the more severe 10% impairment. For the more severe 10% impairment level the head dominated while the chest was estimated to be less frequent. It seems that, for the upper body, impairing injury focus can be concentrated to the head. The database in Study I did not provide information on impairment but the study used a method estimating impairment based on information of AIS level and body region (Malm et al., 2008). The method has developed risk matrices based on occupant injury information in Sweden. It was estimated that a certain body region injured to a certain level is comparable in the pedestrian and car occupant situation so that these risk matrices can also be applied to pedestrians. The impairment system follows a nationally applied Swedish model (Försäkringsförbundet, 2004), where, for example, total blindness is set as an impairment of 68%, balance interference 18%, epilepsy with rare outbreaks 10%, and amputation of the tibia 9% impairment. The Swedish Transport Administration (STA) has decided to define seriously injured persons as those sustaining at least 1% impairment (Vägverket, 2008). Since it naturally takes a long time to see the long-term injury outcome the STA (formerly the SRA) has chosen to use the risk matrices proposed by Malm et al. (2008), similar to the method in Study I. Further study is suggested to see if detailed brain injury assessment, where CSDM and SIMon are candidate tools, can be used to assess the risk for long-term disabling injuries.

It was found that the most frequent severe injury/source combination to the upper body was the head-to-windshield area, which was in accordance with Longhitano et al. (2005). The parts of the windshield area responsible for injury were dominated by the structural parts; i.e. the frame including a-pillars and roof edge but also including the area where the instrument panel is situated in the head's line of motion. Similar results were shown by Yao et al. (2008). The large overrepresentation of injury located to this lower glass area compared to the rest of the glass area seems to imply that the instrument panel is too rigid thus producing head injury in the second impact. The distance between the windshield glass and the instrument panel is probably insufficient, possibly in combination with the inability of the glass to absorb enough energy before the second impact. For the most severe accidents head and chest injuries were also caused by the roof edge. These cases were further studied and no single parameter could be concluded as more responsible, but rather a combination of high impact speed, large pedestrian stature and high speed. Head injuries from the hood were all connected to children or short adults, and head-to-hood was the most common injury/source combination for children. Chest injuries were sustained at a rather equal frequency from the hood and windshield areas. It seems that the most effective adult countermeasure would be a windshield countermeasure. The accident data shows that it is preferably designed in a U-shape, covering the lower part of the windshield where the instrument panel is close to the windshield and then extending higher up on the A-pillars.

In conclusion, pedestrian countermeasures for the upper body should be extended from the hood area to include the lower windshield area and the A-pillars. The lower windshield/A-pillar area should primarily focus on fatal and disabling head injuries for adults, but should also consider fatal chest injury for adults and the elderly. The hood countermeasure should consider fatal chest injury for adults/elderly and fatal/disabling head injury for children/short adults.

5.2 KINEMATICS

Full-body simulations were performed (see Study III) with a finite element model of the currently most advanced pedestrian dummy with generic vehicle fronts at 40 and 50 km/h traveling speed. These tests showed a clear sliding effect similar to cadaver tests, which resulted in a higher wrap around distance (WAD) to the head impact relative to the pedestrian height. By subtracting the dummy standing heights from the head impact WAD values in Study III we found that sliding at 30 km/h was close to zero, at 40 km/h 50-255 mm and at 50 km/h 190-350 mm. The 40 km/h values can be compared to PMHS tests by Kerrigan et al. (2009, 2007) which ranged from 205-540 mm for a similar standing height and car geometry. The dummy simulations resulted in less sliding than the PMHS tests, which was also the case for Kerrigan et al. when they performed mechanical dummy tests with the same vehicle. This indicates that the dummies, although showing a clear sliding effect, still underestimate the sliding effect compared to PMHS. Accident data (Figure 4), showed values around 255 mm for an average male, which is at the top end of the dummy simulation values and the lower end for PMHS test values. The accident data is based on average cars in Germany. Accident data, in Study I, confirmed this sliding effect and showed that 60% of severely injured pedestrians have their car-to-head impact at a WAD of less than 2.1 m (current Euro NCAP upper border), and that 86% hit at a WAD of less than 2.3 m.

The head impact speed was in all simulations in Study III lower than or equal to the car impact speed, which was not the case in PMHS tests in previous studies (Kerrigan et al., 2009, Kerrigan et al., 2008, Masson et al., 2007). But similar to previous studies it was, in all cases, lower for the hood impacts compared to windshield impacts. When the shoulder impacts the car the head and neck rotate and the head continues first at high speed but is then, in a later sequence, decelerated by the neck. At impact with a vehicle where the windshield has a different angle than the hood, the head will hit the windshield in the earlier phase of this motion while in the case where the head hits the hood the head velocity has been reduced more by the neck before the impact. This could be a contributing factor to the severity of the injuries in the lower windshield impact. To conclude, this implies that a higher test speed could be necessary in windshield-head impact tests compared to head-impact tests to the hood.

The vehicle pitch that occurs when a car is braking was shown to influence the impact location. This means that for cars with auto-brake systems not only is the impact speed influenced but the head and chest impact location as well. Study III showed that vehicle pitch will result in a more rearward head impact to the car. On the other hand, speed reduction works in the opposite direction, reducing the WAD when speed is reduced. Depending on the car front design this can result in a changed head and chest impact location, either more forward or rearward relative to car structures. This may need to be considered when studying the injury-reducing effectiveness of braking systems, such as brake-assist or autonomous braking. It may also be necessary to consider when determining the coverage area of a windshield countermeasure for an integrated system for a specific car.

Head impact times were dependent on pedestrian size and impact speed. For a 50th percentile male and 40 km/h car impact speed the head impact occurred at approximately 125 to 150 ms after the first impact, in accordance with PMHS tests for similar cars (Kerrigan et al., 2009, Kerrigan et al., 2007, Masson et al., 2007). When the car impact speed was reduced 10 km/h the head impact times were increased by approximately 40 ms, while for an increase of 10 km/h they were decreased by approximately 20 ms. The head of the larger 95th percentile dummy impacted between 10 and 20 ms later than the average sized dummy. Typically, shorter pedestrians and higher impact speed (along with more inclined hoods or higher hood edges) lead to shorter head impact times. This is important to understand when designing secondary countermeasures. See 5.4.2 where this is further discussed.

5.3 IMPLICATIONS FOR CURRENT TEST METHODS

Car occupant safety has improved rapidly during the last decade. Demanding consumer tests have lead to the development of safer cars and car buyers have been willing to pay more for safer cars. However, car buyers may not be willing to spend more for vehicle measures protecting other road users. The driving forces towards safer cars for pedestrians are legal tests or consumer tests where pedestrian protection is part of the full vehicle rating. Study I showed that the current legal/consumer test methods for leg protection regarding test speed, test area and injury criteria seem appropriate. The test speed in general for the head is also appropriate and the legal test area is appropriate for children. For adults the test area does not reflect the true need, and injury criteria may require further development. The test area for the head, which in today's regulations only includes the hood area, should include the lower parts of the windshield area and the A-pillars, in order to address a majority of head injuries. For such a head-to-windshield test, accident data in Study I indicated that the test should be based on a slightly higher car impact speed. Additionally, full-body simulations in Study III indicated that a slightly higher head impact test speed may need to be considered due to the different head kinematics in windshield impact. Developing test tools and injury criteria to better assess brain injury risk should also be considered. The current pedestrian headforms do not allow head rotation other than that caused by friction, while a Hybrid III headform as in Study II could be an alternative, or component test methods where the head and neck interaction is taken into account. Another solution is using full-body dummies. Mechanical dummy tests are, however, expensive and have limited repeatability and limited possibilities to test all areas impacted by different sized pedestrians. Instead, an alternative could be to use full-body simulation which is a method that Euro NCAP is already considering in other areas. Also, the global pedestrian regulation (GTR 9) uses full-body simulations when deployable hood systems are being evaluated. Numerical simulations have good repeatability and allow easy anthropometric changes. Still the finite element models require large computer capacity but the development towards shorter computing times is moving quickly. All these dummies and models could also be used in conjunction with detailed brain models to estimate brain injury. Several advanced brain models have been proposed for research purposes but a promising candidate for car development purposes is the SIMon model which is a less detailed head and brain model and therefore feasible to run on personal computers with short computing times. However, this needs further study. An alternative pragmatic solution is to further study whether countermeasures designed for current test tools and the linear head criterion also minimize rotational loading in a majority of cases. This could be an intermediate solution and then the necessity for new test tools and criteria is reduced until they are further developed to be more valid and feasible.

This thesis has pointed out the need for pedestrian countermeasures in the windshield area. A likely solution for this is an external airbag. The legal and consumer test methods then need to determine if such countermeasures are positioned in time and work in full-body loading. For deployable hoods both the GTR and Euro NCAP have test methods to evaluate these, by using full-body numerical models. A similar test method is then necessary for deployable windshield countermeasures. For any countermeasure to the windshield area it is crucial that the coverage area is appropriate. The likeliness of head impact decreases with higher WAD, and the countermeasure can be concentrated to the lower parts of the windshield. Euro NCAP tests up to a WAD of 2.1 m for the head impact, and that seems to be appropriate since it addresses a majority of severely injured pedestrians (Study III). In the future this could be extended to 2.3 m which addresses almost 90% of pedestrians. Since car geometry affects the sliding of the pedestrian and thereby the head impact WAD, an alternative suggestion is to use numerical full-body simulations to determine the head impact WAD for a 95th percentile male for each vehicle (for the given test speed). This could then be used as the upper limit for windshield countermeasures for respective vehicle. The same simulations could also be used to determine the appropriate head impact speed and angle in headform tests.

Study I and the Preliminary study presented in this thesis showed that, for severe (AIS3+) and fatal accidents, chest injuries are frequent for all adults and especially for the elderly. While the less frequently injured pelvis was considered early in regulation development and is part of the Euro NCAP consumer test, the chest has not been considered in any regulation or consumer test. If this body region were to be considered the test method should include both hood and lower windshield impacts. To address the most frequent impact speed when severe chest injuries occur, Study I suggests basing these tests on a higher car impact speed compared to leg and head tests. Tests should then be based on a car impact speed of at least 50 km/h. Injury criteria for the chest should consider both skeletal and soft tissue injuries according to Study I. Especially older people are frequently chest injured and this more fragile group should be considered when developing injury criteria and thresholds.

To conclude, the author suggests continued use of the pedestrian headform and HIC linear acceleration based criterion as a basis, since it has proven to be a robust method. Since impact location and impact speed is dependent on the car design it is recommendable to introduce full-scale simulations in the test methods to determine impact conditions such as test area and head impact speed and angle prior to experimental component tests. In countermeasure development full-body tests or simulations are recommended to evaluate chest loading and to use brain model simulations to estimate brain loading. These models and dummies need further development to become reliable tools for injury assessment in legal and consumer tests. Further, if the legal test methods aim to address more severely injured pedestrians in the future they should include the lower windshield and A-pillar area. When new car types emerge and become common on the market it is important to carefully study the influence on the kinematics and injury of the pedestrian when impacted. This may lead to a need for new or modified test methods.

5.4 COUNTERMEASURES

5.4.1 Primary safety systems

All studies (I-III) and the Preliminary study presented in this thesis supported the high potential of auto-brake systems. The Preliminary study showed that fatal cases were associated with a high posted speed limit and that braking was rather rare in fatal accidents. Study I showed that severe injury risk was highly influenced by changed car impact speed. If Study I and the Preliminary study are combined one can conclude that not only is a reduced impact speed beneficial, but that auto-brake systems also have, in most cases, a high potential to reduce impact speed since few of the fatal cases included braking. This is in agreement with other studies (Hannawald and Kauer, 2004, Rosén et al., 2010). Study II showed large reductions of head and brain loading when reducing the head impact speed in component tests, and finally Study III showed large reductions of head and chest loading as well as head and brain injury risk by introducing an auto-brake system. To conclude, autonomous braking systems have a high potential for reducing pedestrian head and chest injuries.

5.4.2 Secondary safety systems

It seems that the current trend of bumpers with higher energy absorption capability, combined with a lower stiffener to reduce the bending of the knee and better distribute the load, is a viable way to reduce leg and knee injuries. Euro NCAP-tested cars with these solutions have shown to considerably reduce the knee injury parameters assessed in these tests (Euro NCAP, 2010).

Study II showed that an under-hood distance of 100 mm could reduce head loading, in impacts up to 40 km/h, to acceptable levels both for linear and rotational loading. Study I and the Preliminary study showed that the hood mainly addresses children and short adults. It can be questioned whether the test method of a free-flying Hybrid III headform without neck influence is a representative test tool, but it was assumed to estimate a worst case of head rotation. The studies further showed that when reducing the head impact speed by 10 and 20 km/h, the necessary under-hood distance could be reduced by 20 mm for each 10 km/h step, and maintain a similar level of head loading. This implies that if an auto-brake system reduces the head impact speed by 10 km/h it is as effective as adding 20 mm of deformation distance for a hood with properties similar to the design tested. Although no validated injury criteria were available Study III showed that a deployable hood had the potential to reduce chest loading.

A deployable hood should be designed to be in position early enough for a short pedestrian at high speed as well as staying up long enough for a taller pedestrian at a lower speed. For windshield airbags an even longer stay-up time is necessary while the earliest activation time is also later. For a combined deployable hood and windshield countermeasure, preferably different activation times and stay-up times can be used. Further, the head impact timing correlation of impact speed actually helps the contact sensor design. At higher impact speed, the necessary sensing time is shorter due to higher impact force and higher bumper intrusion speed.

Study I and the Preliminary study clearly showed the need for countermeasures in the windshield area. To be cost effective and obstruct as little as possible of the driver's sight in case of faulty activation it is important to limit the size of a windshield protection device. The studies concluded that these countermeasures should be concentrated to the lower windshield area (instrument panel area) and the a-pillars. It is necessary to design each such countermeasure for the individual vehicle; a small vehicle needs protection higher up on the a-pillars. Small cars may even need to consider the roof edge as well. It was found in Study I that a coverage area, of a countermeasure, up to 2.1 m WAD (today Euro NCAP upper border) addressed 60% of AIS3+ head injuries. If increasing the WAD to 2.3 m almost 90% were then addressed. Windshield countermeasures should primarily be designed to mitigate head injury but should also consider chest injury mitigation, especially for the lower parts. Study I showed the high potential of windshield protection, when it estimated that a combined system of leg-to-bumper, chest/head-to-hood and head/chest-to-windshield protection would address all severe injuries for 73% of those severely (AIS3+) injured when impacted by a car front, while only addressing 44% when not including windshield protection.

In the hood area the necessary energy absorption distances can be achieved by passive measures, by increasing the under-hood distance when designing the vehicle. To achieve this it will require a higher hood surface, which may not be desirable for the car designer for several reasons. Another solution is to raise the hood surface only in case of an accident, which is the idea of the deployable hood, or Active Hood. In the windshield area, it is possible that the instrument panel can be redesigned to meet the energy absorption necessary and that the hood can be extended to cover the lower windshield frame, but the A-pillars are difficult to redesign. The A-pillars need to be narrow in width to maximize the vision of the driver, but also rigid enough to keep the compartment intact in a roll-over accident or in a large animal impact. A future windshield protection system could then consist of an extended deployable hood and A-pillar airbags.

5.4.3 Integrated systems

The primary and secondary safety systems can easily be combined if the primary safety system is an auto-brake system and the secondary system consists of countermeasures for the hood and windshield area. They can be activated in the same way as the individual systems. The passive deployable part of the system should then be designed to provide protection up to a certain impact speed and the auto-brake part should aim to reduce higher speed impacts to that speed. The auto-brake system also reduces injury severity from ground impact at lower impact speeds. The systems then interact to provide good protection in a large speed range. Further, an integrated system with a sensor which would detect a pedestrian impact around 0.3-1.0 second before impact enables an alternative hood deployment technology with a reversible hood lifter, which requires more activation time than what is normally available with a contact sensor. A reversible hood actuator has the advantage of not needing replacement in case of faulty activation. An integrated system with a pre-crash sensor also opens up possibilities for countermeasures in the hood front edge area. These kinds of systems would have the highest potential in sports utility vehicles which have been shown to frequently cause chest injuries in the hood front edge area (Longhitano et al., 2005). One design solution is an airbag, but to be positioned in time would need activation prior to first car contact. Since detection with a pure pre-crash sensor, without contact information, is more challenging there may be a better design potential for reversible solutions in this area.

5.4.4 Potential of countermeasures

Rosén et al. (2010) showed the high potential of auto-brake systems and Fredriksson and Rosén (2010) showed that a primary and a secondary safety system had a comparable potential, and that an integrated system increased the potential. Study II concluded this by showing that both reduced impact speed and increased energy absorption were effective solutions in reducing head and brain injury values and that combined they showed larger reductions. Study III, which used full-body simulations to evaluate primary, secondary and integrated systems compared to reference situations also concluded a high potential for both primary and secondary safety systems, and a further increased potential for integrated systems.

This can be explained by a dose-response model as in Figure 22. It shows the number of collisions (dose or exposure) and injury risk (response) as a function of impact severity (e.g. impact speed). The number of injured (incidence) can be calculated by multiplying the dose and response for each impact speed interval and summing up for all intervals. If impact speed is reduced generally, as with an autonomous braking system, the dose curve will be shifted to the left (arrow 1). If energy absorption is increased in the crash, as with an airbag system, the risk curve is shifted to the right (arrow 2). Since the incidence outcome is determined by multiplying the dose and response, the incidence will be reduced for both systems. If both countermeasures are introduced simultaneously both these effects will work together to further reduce the incidence curve. This is a simplified analysis, assuming that autonomous braking only influences impact speed (arrow 1). Study III showed that impact location is also influenced by braking.

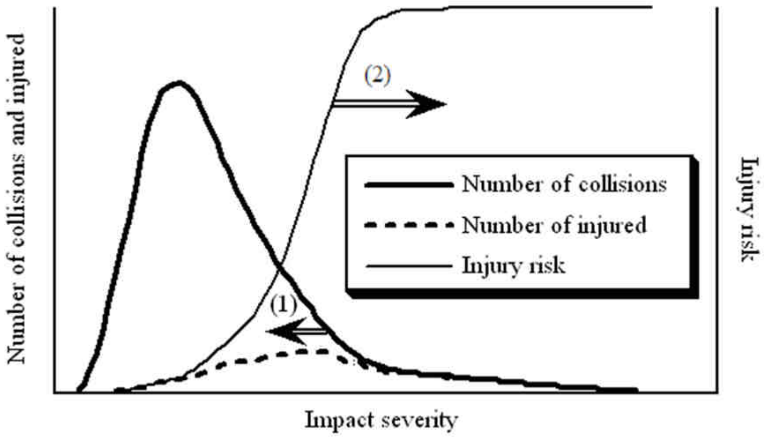


Figure 22. Dose-response model and influence of countermeasures, 1: reduced impact speed (auto-brake), 2: increased energy absorption (deployable devices), (from Kullgren (1998))

All the studies on potential mentioned above used auto-brake systems for primary safety and deployable hoods and windshield airbags for secondary safety. The integrated systems combined these systems with no difference in the individual systems or activation strategies, but taking into account the higher protection potential of secondary safety systems at reduced impact speeds.

5.5 REPRESENTATIVITY TO OTHER PARTS OF THE WORLD

As mentioned, basically all accident studies performed to date have been based on accidents in Europe, Japan and the US. The rest of the world was, more or less, not considered, mainly due to a lack of detailed accident investigations. To gain sufficient quality and detail in accident investigations, trained accident teams need to visit the accident scene shortly after the accident. This is expensive and has limited this activity to a few locations in high income countries. Still, the rest of the world has higher or much higher proportions of pedestrians killed in traffic accidents and account for as much as 95% of global pedestrian fatalities (Naci et al., 2009). These countries have different mixes in their vehicle fleets which may cause the conclusions in this thesis, based on passenger cars, to lack validity in these countries. Body height can differ which influences the kinematics and car parts impacted. Infrastructure may also differ with less separation of traffic elements. When countries develop it is likely they will see the same development as in western countries, towards a larger proportion of cars and an infrastructure with greater separation between elements. It is even likely that the population's average stature increases. This implies that the results from this thesis may, in the future, also be valid for these countries. In some countries, such as China and India, the car population is rapidly increasing. Introduction of pedestrian countermeasures on new cars in these countries, would therefore quickly affect the market in terms of real traffic safety potential. When the market matures it will take longer to introduce new countermeasures that influence traffic safety for a majority of the population. This, combined with the high numbers of pedestrian fatalities in these countries today, leads to a high injury-reducing potential if pedestrian countermeasures are introduced in these countries.

This thesis focused on the vehicle and the possible countermeasures that can be developed to decrease pedestrian casualties. It is important to note however that development of infrastructure, policies and vehicle design must go hand-in-hand to reduce the high pedestrian casualty numbers in developing countries (Mohan, 2008).

5.6 FUTURE RESEARCH NEEDS

All existing pedestrian regulations limit head protection requirements to the hood area. Also, all research for pedestrian injury mitigation in the hood area has been focused on head injuries, historically as well as currently. This thesis showed that chest injuries from the hood area were more frequent than head injuries from this area in severe (AIS3+) and fatal accidents. Therefore study of the chest injury mitigation potential of current hood systems is recommended. It is necessary to develop test methods to achieve this, including impactors or dummies as well as injury criteria for this type of impact. It is possible that the recently developed hood systems already provide protection to the chest or can easily be redesigned to mitigate both head and chest injuries. Many car models will be developed in the near future to meet regulations and reach high scores in NCAP tests. These car models have a long life span, so if it is possible to optimize the hood for both head and chest injury mitigation this research should be quickly initiated.

The biggest need, however, was for the windshield area in head and brain injuries. The introduction of pedestrian protection as part of the full vehicle rating in Euro NCAP is likely to lead to the introduction of windshield countermeasures. This thesis showed the importance of considering brain injury and rotational loading in this countermeasure design. Therefore research on test methods capable of evaluating brain loading is necessary. Further research is also suggested to study whether detailed brain injury assessment can be used to estimate the risk of long-term disabling injuries. Finally, results of this thesis suggested that head impact to the windshield may be associated with higher head impact speed than hood impact. These results were derived from a limited range of car types, and further research is suggested to study this in a broad range of car types.

We see a current trend towards smaller cars to reduce fuel consumption. Smaller cars have a different geometry, which will influence kinematics, but may also need to be stiffer due to the short energy absorption distance available in frontal crashes. Electric cars will also be common in the near future, and will be likely to have both different geometry and structures. While basically all internal combustion engine cars have the rigid engine in front, electric cars have a larger design freedom to locate the drive train in other parts of the car body. This provides the possibility to design the front end differently, both regarding geometry and stiffness, than in today's cars. Research should be performed to gain understanding of these car designs and how pedestrian protection can be optimized for these car types.

As mentioned, this thesis and previous studies have concentrated on the situation in the western world, mainly due to lack of detailed data from pedestrian accidents in other countries. Many of these countries have high numbers of pedestrian injuries and fatalities and it is important to investigate accidents in these countries to understand how to best mitigate injuries. Since these countries have different vehicle mixes it will likely lead to the need for studying pedestrian impact to other vehicle types, such as trucks, buses or motorcycles (Mohan, 2002).

Pedestrians have been the dominant vulnerable road user group studied. There are indications that bicycle use is increasing (Thiemann-Linden, 2010), especially in larger cities due to higher fuel prices and raised environmental awareness of the population. Pedestrians and cyclists already make up roughly half the traffic fatalities in urban areas in EU countries (EC, 2010b), with the risk that fatalities will increase with increased bicycle use. It is therefore important to study bicyclist accidents to understand how the proposed pedestrian countermeasures can be designed to mitigate injuries for bicyclists in vehicle impacts as well.

In previous studies and this thesis the potential of pedestrian countermeasures have been estimated using accident data or experimental/numerical approaches. In future estimations, of the potential of countermeasures for pedestrians and other vulnerable road users, the analysis should combine accident data and experimental/numerical simulations to enable a more accurate estimate of the potential benefit of these systems.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

This thesis found that to mitigate upper body pedestrian injuries in severe and fatal accidents, both primary countermeasures reducing impact speed and secondary countermeasures for the hood and windshield areas are beneficial and complement each other to increase protection potential. The windshield countermeasure can be concentrated to the structural parts and the hood and windshield countermeasures should be designed to mitigate head/brain and chest injuries. Special consideration should be taken to design for elderly pedestrians. Specifically, the following conclusions can be made:

- Of all surviving pedestrians 31% were estimated to sustain a permanent impairment and 5% a more severe impairment. The head was found to be most susceptible to severe impairment.
- Contrary to present regulations, this thesis found that head-to-windshield was the dominant upper body injury/source combination for severe (AIS3+) and fatal accidents, followed by chest-to-hood/windshield. However, the current regulations cover the major child upper-body injury/source combination, head-to-hood.
- Injuries in the windshield area were concentrated to the frame and the lower glass area where the instrument panel is situated in the head's line of motion. The current windshield upper head impact border in consumer tests addresses the head impact locations of 60% of severely head-injured pedestrians. If this area is extended 200 mm higher, 86% are addressed. Most common impact speeds (modal values), resulting in severe injury, were approximately 45 km/h for the head-to-windshield area and 50-55 km/h for chest impacts to the hood and windshield areas.
- An impact speed reduction from 50 to 40 km/h reduced the risk of severe head or chest injury by approximately 50%, and from 50 to 30 km/h risks decreased 75-80%. Since the thesis also showed that braking action from the driver was rare in severe accidents, the potential of an auto-brake system to mitigate pedestrian injury in real accidents is high.
- The same hood design (in stiffness and under-hood distance) developed to meet current head loading requirements (HIC in linear loading), also proved to be effective in reducing brain loading to low levels (CSDM in combined linear/rotational loading). Further, for the hood design tested, a 10 km/h head impact speed reduction was comparable to a 20 mm increase in under-hood clearance in regard to head and brain loading reduction, and if combined these measures complemented each other to further reduce head and brain loading.
- Both primary (auto-brake) and secondary safety measures (deployable hood and windshield airbag) showed a high potential for reducing head and chest loading in full-scale dummy simulations. However, integrated systems further increased the potential.

The main conclusions in the thesis are summarized and presented in a flow-chart, Figure 23. The injury outcome is highly dependent on impact speed (1a) and impact location (1b). The most common impact speed is found in accident data (1a) and can be used as design speed to optimize passive countermeasures. A primary safety countermeasure that detects pedestrians in danger and autonomously brakes the car (2a) and secondary countermeasures for the head and chest in the hood and windshield areas (2b) are good candidates for pedestrian protection. The separate systems have a high potential to reduce injuries, and if combined into an integrated system the potential is further increased (3).

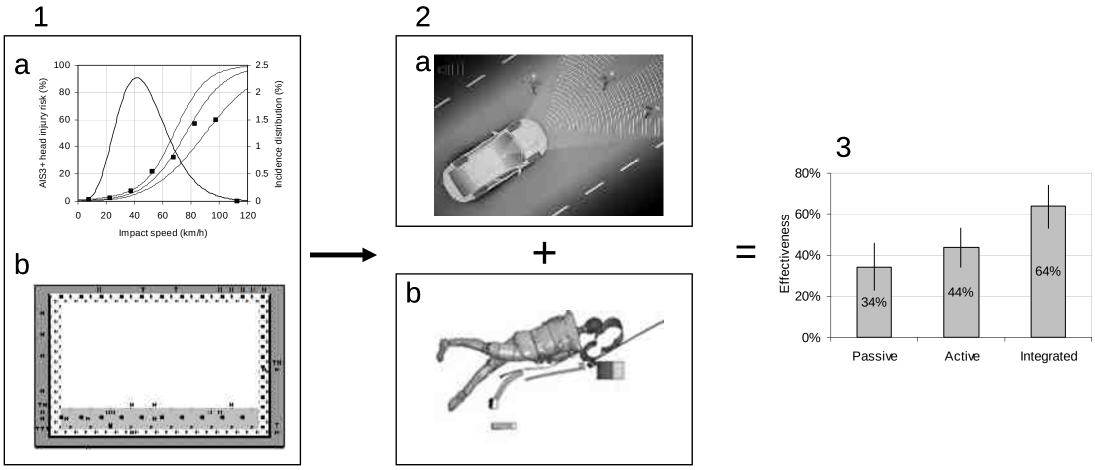


Figure 23. Flow-chart of main findings in thesis: 1a) Impact speed and risk/incidence, b) Injurious impact locations in windshield area, 2a) Primary countermeasure, and b) secondary countermeasure, 3 Effectiveness of a primary, secondary and integrated system

6.2 RECOMMENDATIONS

To reduce pedestrian injuries and fatalities it is necessary to develop less dangerous cars and car fronts in pedestrian impacts.

- If legal tests are to be extended into new areas of the car, the tests should include the structural parts of the windshield area to maximize the injury-reducing effect. It is then suggested to continue using the pedestrian headform and HIC as the foundation, but to complement these tests with full-body simulations and brain models to estimate brain loading. Developing a chest injury assessment for the hood and windshield tests should also be considered, where injury criteria should take the more fragile elderly people into consideration. Full-body simulations are also suggested to evaluate safety system performance in more realistic loading conditions. These simulations could then be used to evaluate chest forces and head rotational loading. Until validated tools and injury criteria are developed for the brain and chest, this could be a pragmatic solution to consider for brain and chest loading. Full-scale simulations are also recommended to determine impact conditions, such as the upper limit of the test area and head impact speed and angle, prior to experimental component tests.

- Secondary safety systems, such as deployable hoods and windshield airbags, are design solutions that can address these requirements. Windshield airbags, should concentrate on protection from impacts to structural parts of the windshield (i.e. A-pillars and lower frame and glass area in close proximity to the instrument panel) maximizing protection potential, making the design more feasible and minimizing the risk of obstructing the driver's view in case of false activation. Such an airbag could then preferably be U-shaped with the lower parts covering the lower windshield/instrument panel area extending up on each side to cover the A-pillars. If the airbag can be extended 200 mm higher than the current (consumer test) standard 2.1 m the percentage of pedestrians addressed is raised from 60% to almost 90% of severely injured. Windshield countermeasures are potentially more effective than countermeasures for the hood area which is in focus in today's regulations. Hood countermeasures should still be included since they address severe chest injury for adults and the elderly as well as head injury for children. Car designers should strive to redesign the instrument panel, and if a deployable hood is designed to extend and protect from impact to the lower windshield frame, windshield airbags can be limited to the A-pillars.
- Secondary safety systems should preferably be complemented by primary safety systems, such as autonomous braking, to give a higher combined protection potential than an individual system. Secondary systems should be optimized for protection at the most common impact speed. This thesis indicates that a car impact speed of 45 km/h for head-to-windshield and 50-55 km/h for chest-to-hood/windshield are appropriate design speeds to optimize countermeasures for mitigation of severe (AIS3+) injuries. Above those impact speeds auto-brake systems should aim to reduce the impact speed to those speeds.
- Since pedestrian protection by itself has not been proven to be a sales argument for new cars, it is important to provide other incentives to car buyers to select more "pedestrian friendly" cars. The newly introduced combined rating of occupant and pedestrian protection in Euro NCAP is an important step and should be followed by other consumer organizations world wide. Consumer test organizations should also consider developing a combined rating of primary and secondary pedestrian safety systems, such as auto-brake systems and in-crash protection systems.

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"*The difference between what we do and what we are capable of doing would suffice to solve most of the world's problem*." *(Mohandas Gandhi)*

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