THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

in

Machine and Vehicle Systems

Integrated Pedestrian Safety Assessment

A Method to Evaluate Combinations of Active and Passive Safety Systems

NILS LÜBBE

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2015

Integrated Pedestrian Safety Assessment
A Method to Evaluate Combinations of Active and Passive Safety Systems

NILS LÜBBE
ISBN 978-91-7597-296-1

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 3977
ISSN: 0346-718X

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

Chalmers Reproservice
Gothenburg, Sweden 2015

Integrated Pedestrian Safety Assessment
A Method to Evaluate Combinations of Active and Passive Safety Systems

Nils Lübbe
Division of Vehicle Safety, Department of Applied Mechanics
Chalmers University of Technology

Abstract

Pedestrian road casualties are a major concern in many countries. Vehicle safety systems attempt to reduce casualties and the accurate assessment of such systems is therefore essential. Passive safety assessment is well established, and additional active safety assessment has recently emerged. However, assessment methods accounting for the interaction between active and passive safety do not exist in today's regulatory or consumer testing. An integrated safety assessment can help reduce pedestrian casualties more effectively and efficiently by taking information gained through active safety assessment into consideration and modifying the passive safety assessment accordingly.

This research develops an integrated pedestrian safety assessment method and demonstrates its use in assessing combinations of passive safety and the active systems of Automated Emergency Braking (AEB) and Forward Collision Warning (FCW).

Firstly, a method was developed that predicts causality costs for a vehicle using data from passive safety and AEB evaluations. Casualty costs were then compared for vehicles with good, average or poor Euro NCAP passive safety ratings in combination with an A-pillar airbag and an AEB system. The results show that the AEB system has a safety benefit broadly equivalent to increasing the Euro NCAP passive safety rating from poor to average or average to good, and that the estimated benefit of the A-pillar airbag exceeded that of the AEB system.

Secondly, the method was extended to assess FCW systems. Data to model driver reactions required for the FCW assessment was obtained in a volunteer study. Applying this method for different types of FCW systems showed that such systems can, but do not necessarily, provide benefits similar to those of AEB systems. An early activating FCW system with a haptic (brake pulse) warning interface was as effective as an AEB system in reducing casualty cost.

These assessments of AEB and FCW systems measure True Positive performance, which is, broadly speaking, the performance of an activated system in situations in which activation was needed. Additional False Positive requirements are proposed to ensure that active safety systems are not activated too early; a threshold of what could be considered too early was developed from the quantification of driver comfort boundaries in volunteer studies.

The integrated assessment method proposed has the benefit of estimating overall safety performance with a single indicator, casualty cost, making results for different vehicles easily comparable. Furthermore, as the method aims at a realistic assessment of a vehicle's ability to protect pedestrians, all body regions and injury severities, all relevant impact speeds, as well as impact kinematics and interdependencies are taken into account, making this the most complete method currently developed. However, since the method relies on the testing of a vehicle's active safety systems in representative scenarios, and on the testing of its passive safety with existing impactor tests, limitations of these existing test procedures will necessarily have an impact.

It is suggested that the proposed integrated pedestrian safety method be implemented in consumer testing to assess the total benefit offered by any combination of active and passive safety technology. In addition, findings suggest that testing for active safety should be expanded to FCW systems and, furthermore, that False Positive tests should be implemented. In the test scenarios already in use for assessment of speed reductions, AEB and FCW system activation before comfort boundary timing should be discouraged. With these proposals implemented, assessment would more accurately reflect the total safety benefit offered by different systems and therefore aid the development and proliferation of the most effective and efficient pedestrian safety systems.

Keywords: pedestrian, assessment, integrated safety, False Positive, driver behaviour, reaction time, comfort boundary, AEB, FCW, airbag

Acknowledgements

The work presented in this thesis was conducted at the Division of Vehicle Safety, Department of Applied Mechanics, Chalmers University of Technology in Gothenburg, Sweden; at Toyota Motor Europe, Technical Affairs Planning Department, Zaventem, Belgium; and at Toyota Motor Corporation, Advanced Control System Development Division, Susono, Japan.

I would like to thank all those who have funded my research: Toyota Motor Europe and the Folksam Research Foundation (Forskningsstiftelse) for sponsoring my PhD studies; the European Union Seventh Framework Programme (FP7/2007-2013) which provided funding for Studies I and II under grant agreement n° 285106; Autoliv Research for partially sponsoring Study IV; and finally Toyota Motor Corporation for allowing me to use their driving simulator in Studies III and V.

As a full-time employee in industry and a PhD candidate living far from the place of study, I received help from many people whom I would like to thank.

I am grateful to my supervisors Anders Kullgren, Johan Davidsson, and Claes Tingvall. Your help in developing my thoughts and making them accessible was most valuable. I very much appreciated the balance in your supervision styles. I could not imagine a better supervision team.

I was given the opportunity to conduct my PhD research in exceptional circumstances. I was given the freedom to teach (or not to teach) and benefited from creative solutions to fulfil course requirements. I am grateful to all the people at Chalmers who made this possible, either by actively supporting me or by accepting these creative solutions.

I thank my colleagues at Toyota Motor Corporation and Toyota Motor Europe for allowing me to pursue my research interests. In particular I would like to thank Etienne, Nick, Niels and Yoshio for the coffee and ice cream breaks, and for the necessary fun and distraction. I am indebted to Hiroyuki Takahashi for budgeting hours to work on the Integrated Pedestrian Safety Assessment Methodology, and for reviewing all my publications.

I thank my family and friends for being there for me. Thank you, Mélanie, for believing in me, for being my toughest critic and my greatest support.

Contents

List of appended papers

Paper I

Lubbe N, Edwards M, Wisch M. Towards an Integrated Pedestrian Safety Assessment Method. *Proceedings of IRCOBI conference*, Dublin, Ireland, pp. 761–765, 2012.

Division of work between authors: Lubbe proposed the first outline which has subsequently been improved by all authors. The paper was written by Lubbe and reviewed by all authors.

Paper II

Edwards M, Nathanson A, Carrol J, Wisch M, Zander O, Lubbe N. Assessment of integrated pedestrian protection systems with Autonomous Emergency Braking (AEB) and passive safety components. *Traffic Injury Prevention*, Vol.16 Sup1, S2-S11, 2015.

Division of work between authors: Lubbe proposed the outline (adopted from Paper I) and the benefit study on pedestrian airbags that is included in the paper. Zander transferred pre-2013 Euro NCAP pedestrian test results into post-2013 grid data and generated vehicles representative for good, average and poor Euro NCAP performance. All other authors contributed to the collection of further data and relations and their structuring for the method. Lubbe, Nathanson and Edwards wrote the Matlab code. The paper was written mainly by Edwards and reviewed by all authors. Lubbe wrote the study of pedestrian airbags and the section on calculation of injury risk and contributed to all other parts.

Paper III

Lubbe N. Brake reactions of distracted drivers to pedestrian forward collision warning systems. Manuscript submitted for publication.

Paper IV

Lubbe N, Rosén E. Pedestrian crossing situations: Quantification of comfort boundaries to guide intervention timing. *Accident Analysis and Prevention*, Vol.71, pp. 261–266, 2014.

Division of work between authors: Rosén and Lubbe jointly designed the study. Lubbe analysed and presented the data. The paper was written by Lubbe and reviewed by Rosén.

Paper V

Lubbe N, Davidsson J. Drivers’ comfort boundaries in pedestrian crossings: A study in driver braking characteristics as a function of pedestrian walking speed. *Safety Science*, Vol.75, pp. 100–106, 2015

Division of work between authors: Lubbe outlined this study. Lubbe analysed and presented the data. The paper was written by Lubbe and reviewed by Davidsson.

Paper VI

Lubbe N, Kullgren A. Assessment of Integrated Pedestrian Protection Systems with Forward Collision Warning and Automated Emergency Braking. *Proceedings of IRCOBI conference*, Lyon, France, pp. 385–397, 2015.

Division of work between authors: Lubbe outlined this study. Lubbe analysed and presented the data. The paper was written by Lubbe and reviewed by Kullgren.

Definitions and acronyms

ADAC	Allgemeiner Deutscher Automobil Club, a German motorist organization
AEB	Automated Emergency Braking
AEB Group	A consortium for developing AEB test procedures
AIS	Abbreviated Injury Scale
AsPeCSS	Assessment methodologies for forward-looking Integrated Pedestrian and further extension to Cyclists Safety, a European research project
CIREN	Crash Injury Research Engineering Network
EC	European Commission
EEVC	European Enhanced Vehicle-safety Committee
Euro NCAP	European New Car Assessment Program
FCW	Forward Collision Warning
FE	Finite Element
GIDAS	German In Depth Accident Study
HARM	A monetary measure of human and material crash harm
HIC	Head Impact Criterion, a unit to assess violence of the head impacts
ISS	Injury Severity Score
ITARDA	Institute for Traffic Accident Research and Data Analysis
JNCAP	Japanese New Car Assessment Program
MADYMO	MAthematical DYnamic MOdels, a Multi-Body Human Body Model
MAIS	Maximum Abbreviated Injury Scale
NHTSA	National Highway Traffic Safety Administration
PCM	Pre-Crash Matrix
PreEffect-iFGS	Assessment method Predicting Effectiveness of integrated Fußgängeschutzsysteme (German for pedestrian protection systems)
Rpmi	Risk of permanent medical impairment
RSC	Rating System for Serious Consequences
STRADA	Swedish Traffic Accident Data Acquisition
THUMS	Total Human Model for Safety, a FE Human Body Model
TTC	Time to Collision, calculated as velocity divided by distance
VERPS	Vehicle Related Pedestrian Safety
vFSS	Advanced Forward-Looking Safety Systems, a working group developing AEB test procedures
VRU	Vulnerable Road User, defined as pedestrians, cyclists and motorized two-wheelers

1 Introduction

Pedestrian causalities are an important part of the overall number of road traffic causalities and require attention. Active safety systems that inform or warn the driver of an imminent collision or automatically initiate braking of the vehicle have recently been coming to the market, joining longer established passive safety systems which provide energy absorbing structures to reduce the violence of an impact.

Assessment procedures for passive safety systems are well established in regulatory and consumer testing. Methods to quantify the benefit of active safety systems have already been developed and are to be included in the 2016 program of the consumer testing organization Euro NCAP. Assessment of integrated pedestrian safety, which is the combined effect of active and passive safety systems in the same collision, is therefore in its infancy.

The aim of this thesis is to develop a new method to assess the integrated pedestrian protection offered by passenger cars including both active and passive safety systems.

This introductory chapter first characterises pedestrian accident scenarios and injuries (Section 1.1) and then gives a brief overview of injury mitigation strategies (Section 1.2). Section 1.3 deals with the question of how safety can be measured on different injury scales and is followed by a review of current practice in assessment of active, passive, and integrated safety in Section 1.4. These assessments can be conducted as hardware tests or simulation and concern themselves with the injury reduction that safety systems offer during necessary activations (in collisions or near-collisions). In Section 1.5, theory and practice of the assessment of unnecessary activations are reviewed.

Chapter 2 details the scope and aims of this thesis, based on the best practice and research gap identified in the introduction. Chapter 3 summarises Papers I to VI and introduces their key findings. Papers I, II and VI develop and apply a method to assess the integrated pedestrian protection of passive safety and Automated Emergency Braking (AEB) offered by passenger cars. Paper III studies driver behaviour to enable Forward Collision Warning (FCW) assessment. Papers IV and V quantify driver comfort boundaries for pedestrian encounters and suggest thresholds to differentiate between necessary and unnecessary safety system activations. Chapter 4 discusses the developed integrated assessment method in the light of existing knowledge and highlights implications, limitations and some future research needs. Chapter 5 concludes this thesis stating its contribution to knowledge.

1.1 Epidemiology (accident and injury types)

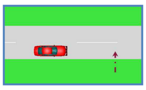
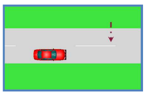
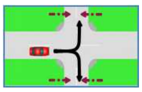
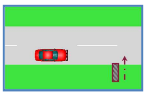
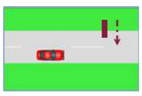
Pedestrian fatalities and injuries are of major concern in many countries and need to be addressed. In the European Union (EU-24), 20% of all fatalities in 2010 were pedestrians (Pace *et al*., 2012). In the USA, pedestrians accounted for 14% of all fatalities in 2012 (NHTSA, 2014). In Japan 2010, pedestrian fatalities represented the highest proportion of fatalities among all means of transport, at 35% (ITRADA, 2012).

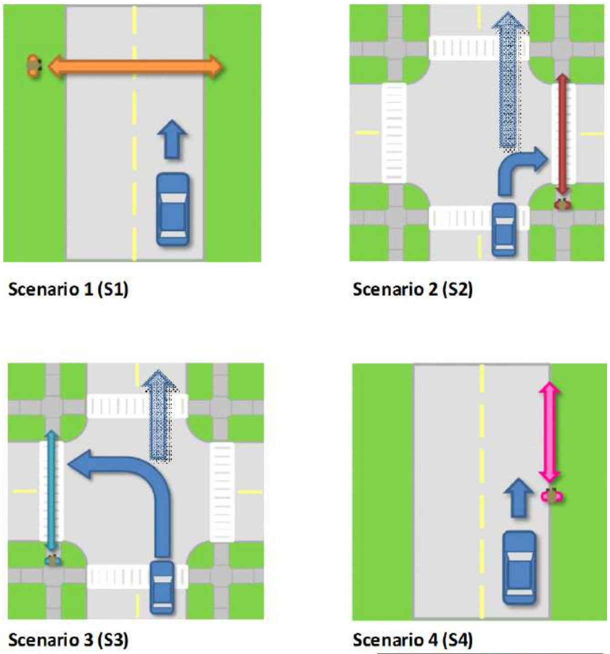
Passenger cars are the dominant collision partner for pedestrian fatalities: 46% in Japan in 2010 (excluding mini-sized cars; ITARDA, 2012), 44% in the USA in 2012 (NHTSA, 2014), and 65% in Germany in 2010 (Wisch *et al*., 2013). Protection of pedestrians by passenger cars is, therefore, of importance.

A majority of pedestrian fatalities occur in darkness: 51% in the EU in 2010, 70% in the USA in 2012 and 69% in Japan in 2009 (Pace *et al*., 2012; NHTSA, 2014; ITARDA, 2011). When not only fatal but also serious injuries are taken into consideration, the majority of injuries are sustained in daylight conditions: 67% in the UK, 2008-2010 and over 60% in Germany, 2008-2010 (Wisch *et al*., 2013).

Most pedestrian causalities involve a vehicle moving straight ahead and a pedestrian crossing the road (Yanagisawa *et al*., 2014; Wisch *et al*., 2013; ITARDA, 2012). Exact numbers depend on the region and severity of injury under consideration. Wisch *et al*. (2013) developed 6 distinct accident scenarios with weighting factors (the proportion of accidents that can be considered similar to a specific scenario compared to all accidents at the injury severities "Killed and Severely Injured (KSI)", "Fatality" and "All Casualties") for Europe. The scenarios are presented in Table 1 and account for about 50% of all accidents involving pedestrians. For the USA, Yanagisawa *et al*. (2014) indicated 4 priority scenarios. Figure 1 depicts these scenarios with corresponding fatality rates.

Table 1. European accident scenarios adopted from Wisch *et al*. (2013)

ID	Accident scenario	Description	EU-27 Weighting Factors		
			KSI	Fatalities	All casualties
1		Crossing straight road, near-side, no obstruction	15%	13%	11%
2		Crossing straight road, off-side, no obstruction	12%	17%	9%
3 & 4		Crossing at junction, near- or off-side, vehicle turning across traffic or not across traffic	5%	2%	4%
5		Crossing straight road, near-side, with obstruction	5%	2%	3%
6		Crossing straight road, off-side, with obstruction	4%	2%	3%
7		Along carriageway on straight road, no obstruction	8%	10%	7%



		Fatalities	%Fatalities
S1	Going Straight & Crossing Road	7,548	64%
S2	Turning Right & Crossing Road	59	1%
S3	Turning Left & Crossing Road	141	1%
S4	Going Straight & Along/Against Traffic	2,888	24%
	OTHER SCENARIOS	1,156	10%
	Total	11,792	100%

Figure 1. US accident scenarios Yanagisawa *et al*. (2014)

By looking at in-depth studies of injuries sustained in pedestrian accidents, the importance to pedestrian safety of various body regions and vehicle areas can be identified. Most severe injuries are to the head, followed by chest injuries (including thorax, abdomen and spine) and lower leg injuries. These findings were obtained using data from the German In-Depth Accident Study (GIDAS) (Liers and Hannawald, 2009; Liers, 2010; Fredriksson *et al*., 2010), the French Rhône Trauma Registry (Martin *et al*., 2011) and US Crash Injury Research Engineering Network (CIREN) (Mueller *et al*., 2012). Exact injury frequencies differ with study design and data source as depicted in Figure 2. For example, Liers (2010) sampled pedestrian accidents with the vehicle front of passenger cars at impact velocities up to 40 km/h while Fredriksson *et al*. (2010) excluded Sports Utility Vehicles but included all impact velocities.

Findings from studies at different injury severities measured according to the Abbreviated Injury Scale (AIS) are presented in Figure 2. Higher AIS levels indicate a higher probability of not surviving the injury. The scale extends from 0 (no injury) to 6 (untreatable) (AAAM, 2008). A "+" as in AIS2+ indicates that injuries at the AIS 2 level and higher were studied. It can be seen that head, chest and lower leg are the most injured body regions. The share of injuries to the chest increases notably with injury severity (from AIS2+ to AIS3+). As severity increases further, head injuries gain importance while injuries to the extremities lose importance, as these never (lower leg, upper extremity) or rarely (pelvis) exceed the AIS3 level.

Head injuries are most commonly sustained in an impact with the windshield area while lower leg injuries are most commonly found in impacts with the bumper structure. Bonnet and ground impact are the most common cause of chest injuries (Liers and Hannawald, 2009; Liers, 2010; Fredriksson *et al*., 2010; Mueller *et al*., 2012).

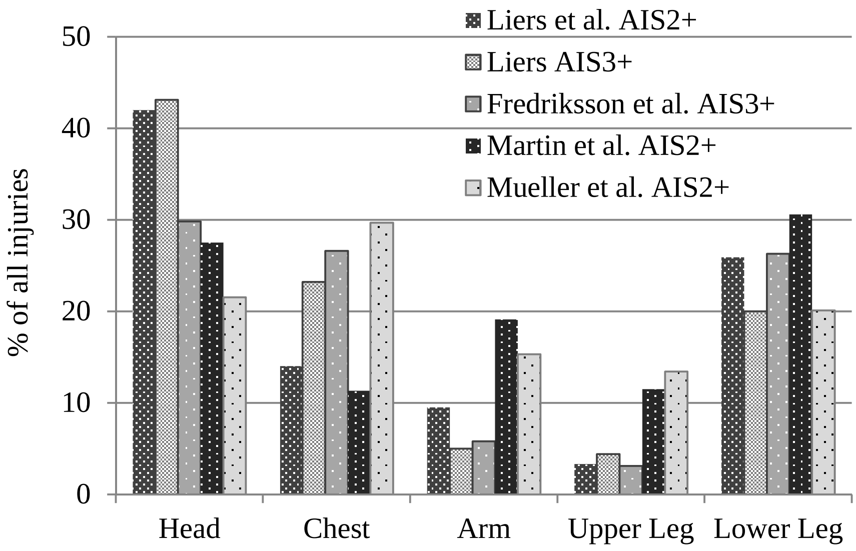


Figure 2. Injury frequency by body region

1.2 Possibilities for protecting pedestrians

A reduction of pedestrian casualties can be achieved through improved traffic design, including road design, vehicle design (as collision partner), protective devices (e.g. helmets) and education (DaCoTa, 2012). Ideally, this is done with consideration given to interdependencies, and with a well-defined goal as, for example, in the Swedish Vision Zero approach (Tingvall and Haworth, 1999; Trafikverket, 2012).

Road design measures may include setting appropriate vehicle speed limits and enforcing them, creating safe walking routes separated from other traffic modes, and safe crossing facilities. Education aims to improve skills and behavioural patterns. Vehicle design measures may include energy absorbing car fronts, and under-run protection on trucks (Wittink, 2001). Detailed descriptions of how vehicle design can be modified to improve predicted pedestrian protection can be found, for example, in Bachem (2005) and Lawrence *et al*. (2006). In these studies, the focus was on passive safety, that is, the design of energy absorbing structures to mitigate injury outcome during the collision and contact phases. In addition, Fredriksson (2011) and Hamacher (2014) study solutions that improve predicted pedestrian protection by passive and active safety systems, thereby also including technology for impact speed reduction prior to a collision. Assessment of the protection offered by these systems in isolation and in combination is needed to guide the prioritization of systems and to select effective combinations.

1.3 Injury scales to assess pedestrian safety

The level of pedestrian safety offered by vehicles can be measured in various ways, one of which is as the inverse of risk. Risk is the chance of an adverse event with specific consequences (Burgman, 2005). Thus, both the likelihood and severity of consequences define a risk. The consequences in vehicle-to-pedestrian encounters range in severity from non-injury collision avoidance to fatal collisions. Various scales to assess pedestrian safety have been developed.

Choosing which scale to use to assess safety performance and to define targets for desired performances has a direct influence on the prioritization of safety technologies and on the degree of safety performance consequently achieved (Tingvall *et al*., 2013). Those scales most widely used for target setting are likely to receive more attention than others.

Road traffic fatalities have been targeted for many years in the EU (OECD, 2008) and are central in the United Nations Decade of Action for Road Safety (WHO, 2011). As the number of fatalities decreases, a focus on nonfatal outcomes leading to long-term consequences becomes more of a priority (Stigsson *et al*., 2015).

The most widely used injury scale in trauma research is the Abbreviated Injury Scale (AIS), which categorizes every injury in each body region according to its immediate threat-to-life. The AIS ranges from 0 "non-injured" to 6 "currently untreatable" (Schmitt *et al*., 2004). However, the AIS has been criticized as being inaccurate and insufficient. Weaver *et al*. (2013) suggest that the AIS fails to capture the fatality risk associated with some of the most frequent injuries sustained by car occupants and that injury classification using Mortality Risk Ratios instead of the AIS provides a better quantification of fatality risk. Tingvall *et al*. (2013) note that the immediate outcome of road traffic accidents (as measured by AIS) might differ from the long term outcome.

Despite these criticisms, the AIS nevertheless remains the basis for most vehicle assessments. Euro NCAP scoring for pedestrian safety is to a large extent based on AIS2+ injuries. For example, Euro NCAP's passive safety lower and upper leg assessment thresholds are based on AIS2+ level injury risk curves (EEVC, 2002). Scoring for active safety (Schram *et al*., 2015; Euro NCAP, 2015c) mirrors the point distribution based on AIS2+ injuries from Seiniger *et al*. (2014).

As an alternative to rating each injury with the AIS, aggregate metrics capture the implications of combinations of injuries for a person. A person focus might be desirable to design and evaluate safety systems. Several aggregate metrics have been developed and are in use, for instance the Maximum AIS (MAIS), Injury Severity Scale (ISS), the risk of permanent medical impairment (rpmi), Quality of Life Year losses (QUALY), or socio-economic cost, or combinations of them.

The HARM metric (Blincoe *et al*., 2002) has been widely used in cost-benefit analyses. Detailed cost values for injury severity levels and body regions are available for US vehicle occupants (Zaloshnja *et al*., 2004).

The Risk of permanent medical impairment (rpmi) is another aggregate metric that has been widely used in the analysis of road safety benefits, predominantly in Sweden. Rpmi is one part of the Rating System for Serious Consequences (RSC), where both risk of fatality and permanent impairment are combined. (Gustafsson *et al*., 1985) The rpmi for different body regions and AIS levels is based on Swedish insurance data. The impairment risk predicts the frequency of impairment due to road traffic injuries. Thus, rpmi measures loss of health over time (Malm *et al*, 2008). Developed from data for Swedish car occupants (Malm *et al*., 2008), the metrics have also been applied to motorcyclists (Rizzi *et al*., 2012) and pedestrians (Strandroth *et al*., 2011). The ISO 39001 "Road Traffic Management Systems" has defined injury with respect to its long term health impact; rpmi is a metric that reflects these long term consequences.

1.4 Predictive pedestrian safety assessment

Predictive pedestrian safety assessment, the topic of this thesis, concerns methods that aim to predict the impact on safety that safety systems and technologies will have in the future, as opposed to retrospective assessment which establishes effects of systems and technologies observed in accident and incident data.

Predictive safety assessment can be grouped according to the collision phase being studied: Active safety for reduction of collision probability and/or collision severity so that resulting injury risk is reduced in the phase prior to contact; passive safety for the contact phase; and integrated safety for the assessment of pedestrian protection both prior and during the contact phase. Post-crash safety, characterizing measures after the collision has ended, is beyond the scope of this thesis, and further differentiation of active safety into phases according to activation time prior to a collision is unnecessary for its purpose.

In passive safety assessments, models of either a complete body or a specific body region are used to impact a vehicle. Model response is measured and associated with the probability of sustaining injuries. In the regulatory and consumer testing of pedestrian protection, hardware tests of specific body regions are used to rate impactor response against desired or acceptable levels of injury probability.

For active safety, consumer testing commonly takes place on a test track using various models of the collision opponents (targets) to trigger a response from a vehicle under assessment. The ability of a system to avoid collision or reduce impact speed is rated against a desired level of collision avoidance and speed reduction.

Integrated safety assessment procedures, which aim to predict the protection offered to pedestrians by the combined active and passive safety performance of a specific vehicle, have not yet been applied in regulatory or consumer testing, and form the topic of this thesis.

In the following sections, hardware and virtual testing options are reviewed for the assessment of passive, active and integrated safety. Current best practice in regulatory and consumer testing is described.

1.4.1 Passive Safety

Regulatory and consumer testing is conducted with subsystem hardware impactors: Physical models of an adult's head, a child's head, a lower leg and an upper leg are made to impact the vehicle under assessment. Notably, a chest impactor is not in use, despite the fact that the chest is among the most commonly injured body regions (recall Figure 2). An overview of procedures can be found in Carhs (2014). Recent descriptions of Euro NCAP pedestrian safety assessment procedures can be found in Zander *et al*. (2015) for passive safety assessment and Schram *et al*. (2015) for active safety assessment. Further details on test procedures can be found in EEVC (2002); Euro NCAP (2015a); Euro NCAP (2015b); JNCAP (2013); JNCAP (2014a); JNCAP (2014b); EC (2009a); and EC (2009b). The validity of a test depends on its biofidelity regarding impact kinematics and injury assessment; validity is usually debated for each test. Biofidelity has been particularly questioned for the upper leg test impactor used in the test suggested by the Working Group (WG) 17 of the European Enhanced Vehicle-Safety Committee (EEVC) (EEVC, 2002; Cesari, 2008; Hamada *et al*., 2005; Snedeker *et al*., 2003) and is clearly a challenge to achieve for any subsystem hardware impactor tests. These tests cannot replicate full body kinematics, such as the influence of lower leg impact on upper leg impact conditions noted, for example, by Saez *et al*. (2012).

Subsystem hardware impactor tests, on the other hand, have the advantage of being repeatable (Lawrence, 2005). Physical models of a full pedestrian body, such as the Polar dummy, can replicate full body kinematics (Akiyama *et al*., 2001). However, to cover the entire area of possible impacts, a large variety of dummy sizes and test configurations must be used. Such full scale tests are less reproducible and not currently used in regulatory and consumer testing.

Virtual models for testing exist in addition to physical models. These include Finite Element (FE) models of the hardware impactor, of human body regions or full human body models as well as multibody models. The advantage of FE models is that a variety of measurements related to injury generation can be obtained (e.g. plastic strain) without causing physical damage, and can thus be faster and less costly than testing with physical models or Post Mortem Human Subjects. As for hardware tests, the validity of a test depends on biofidelity regarding impact kinematics and injury assessment. The most recent Total Human Model for Safety (THUMS, version 4), a full human body model in FE, has been validated to some extent (Watanabe *et al*., 2012; Paas *et al*., 2015) and has been extensively used for research, but is not used in regulatory and consumer testing except in assessments of deployable bonnets in Euro NCAP (Euro NCAP, 2015b). Virtual testing with FE models of the hardware impactor has been introduced for regulation, but has not as yet been widely applied (Eggers *et al*., 2013).

Since this thesis is intended to be applicable to consumer and regulatory testing, it makes use of subsystem hardware impactors rather than FE models in the assessment of passive safety performance.

1.4.2 Active Safety

Impact speed has a major influence on the likelihood of pedestrian injury; the relationship has been established independently from different datasets (Davis, 2001; Rosén and Sander, 2009; Rosén *et al*., 2010; Tefft, 2011). Current active safety for pedestrian protection mainly constitutes systems warning the driver of an imminent collision, and the automated application of brakes to reduce impact speed. Ideally, the collision is avoided altogether. Consequently, current assessments measure a system's ability to reduce impact speed in pre-defined collision scenarios and score against desired speed reduction (Schram *et al*., 2015; Euro NCAP, 2015c; AEB Group, 2011; Niewöhner *et al*., 2011, ADAC, 2014).

In today's pedestrian safety assessments, and in the one to be introduced in Euro NCAP 2016, tests are conducted as hardware tests, i.e. a vehicle approaches a test target on a test track using a driving robot to control the vehicle (Lemmen *et al*., 2013). In most assessment schemes (Euro NCAP, 2015c; AEB Group, 2011; ADAC, 2014), only the speed reduction performance of AEB is assessed. Only the Advanced Forward looking Safety Systems Working Group (vFSS) has developed a protocol to assess the speed reduction achieved by a warning system (vFSS, 2012a): A driving robot brakes after a warning is issued and after a specified time representing driver reaction time has passed (1 second in vFSS 2012a) as an alternative to automatic brake activation by the system.

In some assessment schemes, an additional, independent score is given for a timely warning, but there is no direct relation between the assigned score and the speed reduction achieved. Euro NCAP plans to rate warnings given prior to 1.2 s Time-To-Collision (TTC) as positive (Euro NCAP, 2015c); Allgemeiner Deutscher Automobil Club (ADAC) also rates system warnings, but the criteria are not publicly specified (ADAC, 2014).

While the focus of current assessments is on speed reduction, some approaches have been developed to assess whether the system activates unnecessarily under normal driving conditions. These approaches are reviewed in Section 1.5.

One limitation of current assessments is that technologies not aiming at immediate speed reduction such as steer avoidance (Toyota, 2013) or adaptive illumination are currently not addressed. Adaptive illumination includes systems that increase night time visibility by adapting the illumination area to road geometry, systems that adapt to other traffic participants by automatically balancing illumination strength and glare, and systems that adapt to hazard levels by indicating imminent or potential collision objects with a spotlight.

As an alternative to hardware testing, various approaches for the simulation of active safety systems for pedestrian protection have been developed. Simulation might allow faster and cheaper testing: Adding a few more test scenarios in an existing simulation environment is likely to be less effort than developing and adding test scenarios in hardware tests. While passive safety tests in Euro NCAP are conducted at one test speed, active safety evaluation is carried out in several scenarios and at several test speeds (Euro NCAP, 2015c; Euro NCAP 2015d), thus increasing the number of tests, and motivating efforts for simulation particularly for active safety systems. As with passive safety testing, the validity and availability of models is a main concern. In particular, accurate models of sensors appear to be lacking (van der Made, 2015).

Simulation approaches might be broadly classified into two types according to the data used to create the traffic situations employed.

The first approach, *single accident reconstruction*, relies on a description of the traffic environment and the paths travelled by vehicles and pedestrians involved in collisions. An example of such a set of collisions useful for the estimation of active safety effects is the German Pre-Crash Matrix (PCM) (Erbsmehl, 2009). Each of the accidents included in the PCM data is then reconstructed in a simulated environment, which allows a replication of the accident with and without the active safety system under study, and establishes the comparative impact a system has on the collisions. The active safety system is usually a simplified model of the real system including sensors, decision making to activate the system, and the influence of an activated system on vehicle dynamics. This approach has been successfully employed, for example by Rosén (2013) using PCM data and by Anderson *et al*. (2012a) using a commercially available software called PreScan (Tass, 2015) to create trajectories from in-depth data collected by the Australian Centre for Automotive Safety Research.

The second approach, *traffic simulation*, creates the paths of the vehicle and pedestrian from the characteristic parameters of traffic or accident data. Thus, both accidents and non-accident situations are simulated. Traffic in countries for which databases with pre-crash paths are not available can be simulated, which enables an analysis of the impact of active safety systems on traffic events not involving a collision. Examples of the application of this method for different geographical regions can be found in Lindman *et al*. (2010), Teraoka *et al*. (2013), Tanaka and Teraoka (2014), and Helmer (2014).

For either approach, the key issues in achieving high validity are the replication of important characteristics of the traffic or accident scenes (Section 1.1) and of the active safety system. Simulation approaches are appealing in terms of the simplicity of obtaining results, once the model is validated; however, it is challenging to establish model validity. Use of simulations in regulation and assessment of active safety systems are further complicated by the fact that these bodies might not have the information required to model a system or to judge its validity. Virtual assessment for active safety, as for passive safety, is not expected to be widely applied in regulatory and consumer assessment of pedestrian protection within the near future. Virtual assessment is not on Euro NCAP's Roadmap 2020 (Euro NCAP, 2015e).

1.4.3 Integrated safety

An integrated safety assessment is needed to account for system interactions and to reduce pedestrian casualties more effectively and efficiently. Protection, as offered by active and passive safety systems, is rarely independent. At least to some extent, the same injuries are addressed and the active safety intervention will influence the passive safety performance. Impact kinematics may change, resulting in a higher or lower predicted probability of injury (Matsui *et al*., 2011; Watanabe *et al*., 2012; Fredriksson and Rosén, 2012).

Integrated safety assessments – assessments that take into account information gained by an active safety system evaluation and modify the passive safety assessment accordingly – are not yet applied in regulatory or consumer testing. Integrated assessments entirely based on computer simulations have however been proposed for vehicle development (e.g. Kompass, 2012). First, the pre-collision phase is simulated with an active safety system intervention. At the time of collision, outputs of the active safety simulation are transferred to inputs to the crash simulation.

Combinations of simulations and hardware testing have also been used to assess integrated safety performance. In an earlier study, the simulation of kinematic changes due to active safety system intervention were combined with hardware tests of passive safety performance in the so-called "Vehicle Related Pedestrian Safety - index" (VERPS-index) (Kühn *et al*., 2005; Kühn *et al*. 2007). The concept was further developed by Hamacher *et al*. (2011), Hamacher *et al*. (2013) and Hamacher (2014) to create VERPS+, which is entirely based on external assessments of active and passive safety systems and no longer requires vehicle-specific simulations of kinematic changes. As the VERPS+ calculation is based on Euro NCAP passive safety testing results, Hamacher (2014) suggests that once Euro NCAP decides on active safety system test methods, the integrated safety benefit estimation offered by the VERPS+-index could be adopted into Euro NCAP. As VERPS+ is based on existing active and passive safety test methods, the validity of these test methods does not need to be proven again.

In the following sections, VERPS and VERPS+ index are described together with other developments for integrated pedestrian safety assessment methods based on the existing Euro NCAP passive safety testing results.

a) Vehicle Related Pedestrian Safety – index and its extensions

This method initially focused on differences in body kinematics for different vehicle shapes, but was later expanded in an early attempt to calculate injury probability for head impacts based on either active or passive safety systems.

The index was originally defined as follows: For a given accident scenario, head impact areas for several pedestrian heights are defined by numerical simulation for each car to be assessed. These areas are then assessed by component tests, resulting in an injury criterion measurement. This measurement is transferred to an injury probability. The index is calculated by weighing the injury probabilities of the impact points for the whole vehicle front according to impact likelihood (Kühn *et al*., 2005).

Hamacher *et al*. (2013) extended the index to include active safety systems and lower leg injury assessment. To assess the benefit of active safety systems, an initial vehicle speed of 40 km/h is assumed. The speed reduction provided by the active safety systems is assessed at 40 km/h, according to an external test protocol, and a new impact speed is determined. Impactor responses for head and lower leg at the new impact speed are estimated with fixed formulas; no additional testing is prescribed. Impact areas and injury probability is calculated for the impact speed after an active safety intervention. Kinematic changes due to impact speed reduction are reflected. The final results are weighted for different accident scenarios with their respective speed and injury reduction.

While this method brought forward the idea of vehicle-specific impact point distribution together with component testing, it has several limitations. Firstly, the method arbitrarily chooses an injury severity level (AIS 3+ level) (Kühn *et al*., 2005; Hamacher *et al*., 2013) to measure the benefit of any active or passive safety system. This means that injuries at a lower injury severity are not explicitly considered (AIS2 risk might however correlate with AIS3+ risk) and that the reduction of injury risk at higher severities is not necessarily reflected. The AIS3+ risk curve used reaches a 100% probability of an AIS3+ injury at a Head Impact Criterion (HIC) of approximately 2500, so, for example, a reduction from HIC 5000 to 3000 will indicate no benefit at an AIS3+ level, whereas some benefit would in fact be expected for the higher severity injuries. Secondly, the method does not assess body regions other than the head and lower leg, and does not combine results into a single indicator. Thirdly, the calculation of the VERPS-index is conducted at one test speed only (40 km/h, which may or may not be reduced by active safety systems), which is derived from accident data, but cannot reflect the safety performance for all the impact speeds at which pedestrian accidents occur. Finally, uncertainty in the data and relations used is not explicitly considered in the calculations.

b) The Searson *et al*. method

The Searson assessment method focuses on evaluating pedestrian safety for head impact at all the impact speeds at which pedestrian accidents occur (Hutchinson *et al*., 2012; Searson *et al*., 2012a). Impact speed frequency data is taken from accident analyses. The injury measurement from a component test, in this case the HIC value from a headform impactor test, is initially obtained for one test speed. Then, using a spring-mass-damper model from Searson *et al*. (2010), it is calculated for all other speeds. Thus, information for the bottoming out depth, when the maximum bonnet deformation is achieved, can be taken into consideration to estimate a steeper increase in HIC values beyond the calculated bottoming out speed (Searson *et al*., 2012b). The HIC values for all impact speeds are then transferred to injury probability, exemplified at the AIS3+ and AIS6 levels. Finally, the injury probability is aggregated over impact speeds. Active safety is considered by modifying the distribution of impact speeds over which injury probability is aggregated according to reductions achieved by AEB systems (Anderson *et al*., 2012b; Searson *et al*., 2014). A specific test procedure for active safety systems to obtain new impact speed distributions is not suggested; the method remains conceptual in this respect.

This method explicitly models the influence of both active and passive safety systems on head injury outcome. Further, the method calculates safety performance for the distribution of impact speeds at which pedestrian accidents actually occur and can therefore assess variations in pedestrian safety for speeds other than the test speed. However, some limitations exist. The impact points used in the passive safety tests are weighted equally, so that the probability of impacting at different locations and the change of this probability with impact speed are not reflected. In addition, there are limits to what the method attempts to model: Kinematic changes due to active safety intervention are not modelled, body regions other than the head are not modelled, and neither does the method model uncertainty.

c) Assessment method Predicting Effectiveness of integrated Fußgängeschutzsysteme

A method called Assessment method <u>Pre</u>dicting <u>Effect</u>iveness of <u>i</u>ntegrated <u>F</u>ußgänge<u>s</u>chutzsysteme (PreEffect-iFGS) to assess the combined effects of active and passive safety systems for pedestrian safety has been described by Schramm (2011) and Roth and Stoll (2011) and is illustrated in Figure 3.

An injury-risk curve at MAIS2+ level for any type of pedestrian injury was calculated from accident data in GIDAS for the average fleet car as the baseline for comparison (grey dashed line in

Figure 3). Vehicle safety is given in reference to injury risk of an average fleet car at a selected test speed (illustrated for 50 km/h in Figure 3). Passive safety systems are assumed to reduce injury risk at the given test speed, while active safety systems are assumed to reduce collision velocity. The reduction of injury risk from the employment of passive safety systems is calculated based on the sets of injury risk curves for different Euro NCAP scores[1]. The blue solid line in Figure 3 represents the injury risk curve for the passive protection level given in the top left of Figure 3. A small reduction in injury risk can be identified comparing grey dashed (lower passive protection level) and blue solid injury risk curves. This reduction is attributed to passive safety systems. Active safety system injury risk reduction is calculated from the change in collision velocity. In Figure 3, the active safety system reduced impact speed from 50 to 35 km/h. This reduction, following the solid blue injury risk curves, is associated with a reduction in injury risk. A specific test procedure to obtain speed reduction for an active safety system is not described; an outline is given of how to obtain these reductions from system simulation of the active safety system under assessment. In a later version, it was suggested that a similar system could be chosen from a library of active safety system simulations based on specifications such as sensor field of view. This library would contain pre-defined speed reductions for a set of simulated active safety systems (vFSS, 2012b). The integrated safety benefit for the combination of active and passive safety systems is the sum of active and passive system risk reduction.

The main advantage of this method is that it covers injuries to all the body regions currently being tested by Euro NCAP. However, this method also has its limitations. The probability of impacting the test points and the change of this probability with impact speed is not modelled. The choice of injury severity level and reference car performance is somewhat arbitrary, and benefits are calculated at one reference speed only. Additionally, the "injury-shift method" lacks validation and a loss of information occurs when combining local (head, upper leg, lower leg) injury risk to a global MAIS risk for passive safety system testing. The depicted injury risk curve at the MAIS2+ level indicates a substantial injury risk at zero velocity, which is explainable from the data and methods used but unlikely to accurately represent reality. As for the other methods, uncertainty is not explicitly modelled.

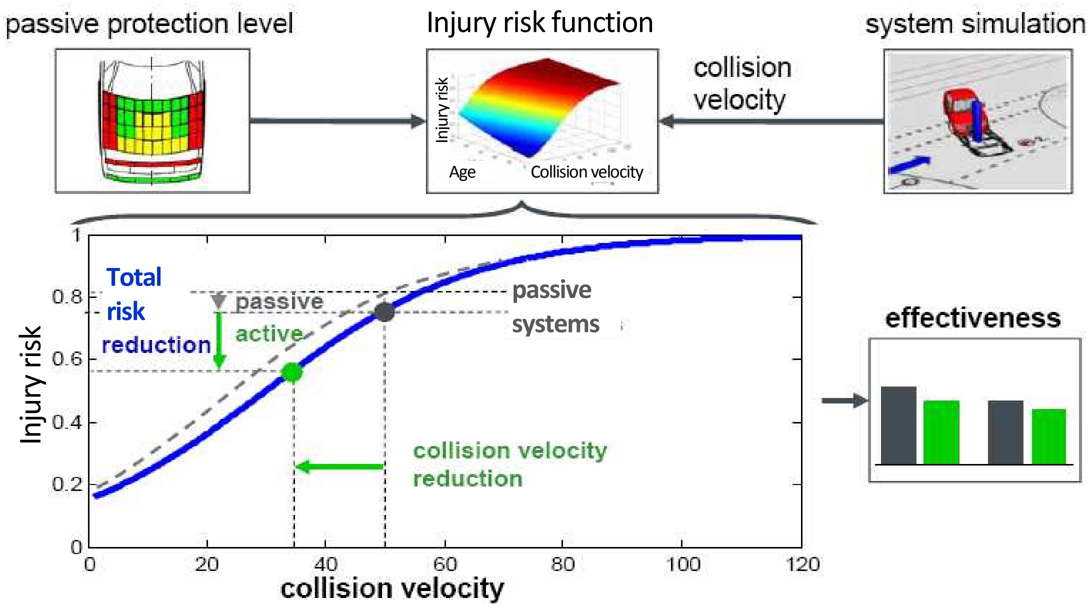


Figure 3. Integrated pedestrian safety assessment method from Roth and Stoll (2011)

[1] The curves are obtained through estimating the effect that Euro NCAP scores have on injury severity, and conducting logistic regression on the estimated new injury outcome. The "injury-shift method" developed by Liers and Hannawald (2009) is used to estimate Euro NCAP score effects. In principle, it is assumed that injury severity is reduced for good Euro NCAP scores. Exact reduction of injury severity depends on the combination of injured body region and test area as well as on the Euro NCAP score in the considered test point.

1.5 Active safety assessment: Balancing True Positive and False Positive activation

The assessment of safety systems today mainly concerns itself with True Positive[2] performance, which is, broadly speaking, the performance of an activated system in a situation in which activation was called for. As described in Sections 1.4.2 and 1.4.3, rating systems for these performances have been developed. All other things being equal, a system that activates earlier will achieve greater speed reduction and a higher score. False Negative activation, where a system does not activate in a situation in which activation was called for, is also included in the ratings as no speed reduction will be achieved and no score will be given. Systems that have a low False Negative activation rate will consequently be given a higher score in today's assessments. The activation of a system when activation is not called for, commonly referred to as False Positive activation, has not been included in Euro NCAP assessments. However, consideration should be given to False Positive performance assessments, as done recently in the assessment methods of ADAC, vFSS and AsPeCSS. Too early an activation can cause driver annoyance and mistrust in the system; mistrust in the system can lead to a deteriorated driver reaction and performance of warning systems (Bliss and Acton, 2003; Abe and Richardson, 2006). Automated systems do not rely on driver reactions, but should nevertheless be designed with False Positive performance in mind. Too early an activation can annoy drivers who might then want to switch the safety system off altogether thereby eliminating safety system performance completely. Furthermore, a driver might not opt for the technology again given the choice at the next car purchase or rental. Balancing True Positive performance assessment (requiring early activation) with False Positive assessment (requiring non-annoying activation) is important to achieve the best overall safety performance.

In the assessment of ADAC, a pedestrian walks on a collision course towards the driving path of the car under assessment but suddenly stops prior to entering the driving path. The conflict situation is thereby resolved independently of any driver action. The aim of this test appears to be to quantify the amount of system activation against a desired level as the car "is supposed to warn and start braking" (ADAC, 2014). Thus ADAC seems to rate warning and brake initiation as desired False Positive and braking to full stop as undesired False Positive. The details of the test set-up and deduction of limits for desired and undesired activation appear not to be publicly available.

In the assessment of vFSS, pedestrians remain outside a collision course but close to the driving path of the car under assessment. Any system activation disqualifies the car from further assessment (vFSS, 2012c). Thus, vFSS has defined a scenario in which any activation is thought to be an undesired False Positive activation.

AsPeCSS developed False Positive tests "with the aim to counteract and unveil too much test-oriented system tweaking" to be carried out alongside tests for True Positive performance (Seiniger *et al*., 2014). In these tests, a similar procedure to that of the True Positive performance test is adopted: A pedestrian is walking towards the driving corridor of a car on a collision course. While in True Positive performance tests speed reduction is evaluated, in these False Positive tests the activation time of a system is assessed. System activation is classified into three groups based on TTC: Firstly, True Positive activation as "mandatory activation", secondly a grey area as "possible intervention", and thirdly an area of False Positive intervention. TTC values are calculated from a presumed deceleration of a pedestrian of $3 m/s^2$ and a safety distance assumed as 1m perpendicular to the driving corridor. In the True Positive activation area, "system reaction is mandatory" as the "pedestrian is not able to come to a complete stop before entering the driving corridor". The grey area "opens variations in timing to act earlier" and describes system intervention at times for which "a pedestrian is able to stop between the beginning of the driving corridor and an additional safety distance to the driving corridor". Finally, a False Positive area describes a "region where prediction already starts to become rather unsure and intervention strategies are often too early in time" and "safety system is prematurely triggered and the unsure intervention is still unsubstantiated and typically not tolerated by the user" (Seiniger *et al*., 2014).

---

[2] A review, discussion, and definition of True Positive, False Negative, True Negative and False Positive can be found in Appendix 2.

Contrary to the procedure of ADAC described above, it was not discussed in the AsPeCSS procedures which systems (AEB, FCW) should activate and how the amount of system activation would relate to activation time. This implies that the thresholds could be understood so that in the first "mandatory activation" any type of system needs to be activated, while in the False Positive area, no system should be activated. Seiniger *et al*. (2014) did not differentiate between AEB and FCW thresholds.

Källhammer *et al*. (2014) reviewed False Positive definitions in the broader context of automotive active safety systems and found that definitions were ambiguous but congruous in that the usefulness of an alarm, dependent on context and driver perception, was seen to be more important than its classification as true or false.

Comfort boundaries can guide such a classification of usefulness (Ljung Aust and Engström, 2011). The comfort boundary divides the states of a feeling of discomfort to the driver and a feeling of comfort. Drivers aim to stay within the comfort zone and take corrective action when they exceed the boundary. The comfort boundary is subject to individual and subjective variations.

Ljung Aust and Dombrovskis (2013) state that the "key enabler for high levels of driver compliance with alerts and warnings is that the system designers and the driver's view of the situation match, i.e. that they share the same definition of where the comfort boundary is. If they do not however, the driver will regard the system's output as a nuisance and general source of irritation."

Comfort boundaries can be used to design False Positive system tests. Using a test scenario developed for True Positive performance tests, the activation of systems could be assessed not only for the speed reduction achieved, but also for their activation timing in relation to the comfort boundaries in that test scenario. Put simply, activation prior to the comfort boundary could be penalized. Systems would then be designed to activate as early as possible, but not before the comfort boundary is reached.

Quantifying driver comfort boundaries in the most common test scenario of a crossing pedestrian can provide the necessary practical False Positive assessment. It can also provide a guide for system designers for appropriate activation timings irrespective of an assessment.

2 Scope and aims

Integrated safety assessment procedures aiming at predicting the pedestrian protection offered by the combined active and passive safety performance of a specific vehicle have not yet been applied to regulatory or consumer testing. The aim of this thesis is to develop a predictive, integrated pedestrian safety assessment method for consumer and regulatory testing and for manufacturers' in-house use.

Since this thesis presents a method that is intended to be immediately applicable to consumer and regulatory testing, it makes use of traditional passive safety tests using hardware impactors. To align with current best-practice in active safety assessment, the tests included in the presented method are also conducted as hardware tests, i.e. a real vehicle approaches a test target on a test track, using a driving robot to control the vehicle.

The method is limited in its scope to active safety systems that operate automatically or warn the driver, aiming for an immediate reaction, and to those systems that aim to reduce impact speed. Thus, while it is likely that other systems such as driver support or steer avoidance have benefits, they lie outside the scope of this study.

The novelty and contribution of this work is the development of a method to meaningfully combine and integrate the results of these hardware tests for an overall assessment of pedestrian protection offered by vehicles. The method prescribes clear test procedures for active and passive safety systems for the specific vehicle under assessment, assesses the protection offered reflecting all impact speeds at which pedestrian accidents occur in the real world, models impact probabilities for different areas on the vehicle front and the change of these probabilities as a result of active safety system intervention, considers all body regions of a pedestrian potentially injured, and combines everything into a single indicator of the total pedestrian safety performance.

Furthermore, specific thresholds for an assessment of unnecessary activation are proposed, ensuring that active safety systems are not activated too early which could be annoying to drivers and prevent the desired reduction of impact speeds.

The specific research aims were:

1. To identify key concepts and issues for integrated pedestrian assessment methods (Paper I).
2. To develop a ready-to-use assessment method for the integrated assessment of passive safety and AEB as one particular active safety system (Paper II).
3. To obtain the data necessary to model driver reactions to FCW systems (Paper III).
4. To investigate driver behaviour when encountering pedestrians in unaided (normal) driving. This was done in order to quantify comfort boundaries, helping to determine the earliest acceptable activation time of active safety systems and to design False Positive tests (Paper IV and V).
5. To extend the integrated assessment method for AEB systems to enable assessment of FCW systems through modelling driver reactions (Paper VI).
6. To assess FCW systems designed with the earliest acceptable activation time (from Papers IV and V) to study whether pedestrian FCW systems have a substantial safety benefit and whether an assessment is indeed justified (Paper VI).

The research was conducted in four main phases:

1. A review of the current state-of-the-art including historical safety performance, current practice and solutions proposed in the literature;
2. Theory development: Anchoring and ways forward for integrated assessment methodologies;
3. Data collection and analysis: Driver simulator studies for FCW driver reaction modelling and comfort boundaries depending on pedestrian speed, and test track study for comfort boundaries depending on vehicle speed;
4. Validation: Implications and robustness of methodology proposed.

The details of the methodology used in each phase can be found in the corresponding paper summaries which now follow.

3 Summary of papers

Paper I outlines the concept and ideas for an integrated assessment method, and Paper II details the ready-to-use method developed for passive safety and AEB. Paper III presents the driver behaviour data needed for the development of a FCW assessment method. Papers IV and V quantify comfort boundaries to set limits to FCW activation time. Paper VI integrates FCW assessment functionality into the method presented in Paper II and illustrates the benefit of using this method.

3.1 Summary of Paper I

Towards an Integrated Pedestrian Safety Assessment Method

AIM. This paper aims to provide the principles for a fully integrated pedestrian safety assessment method.

METHODS and TARGETS. An integrated pedestrian safety assessment is developed using literature review, accident data analysis, computer simulation, hardware testing and validation against real-world data. Targets for the assessment method are defined:

- A fully integrated assessment is necessary to assess the relevant interactions of safety systems. Active safety intervention will influence passive safety performance. Pedestrian kinematics might change and thereby result in a higher or lower probability of injury.
- The method needs to consider all the casualty's (AIS2+) injuries and not just the maximum AIS injury, because it is the combination of all the injuries which determines the outcome for the casualty.
- The benefit needs to be expressed as a single indicator.
- A relevant range of impact speeds should be considered. A single test might encourage sub-optimisation as the structure tested might then not be developed to offer protection at other speeds.
- Both the impact area as well as impact point distribution need to be aligned with actual impact probabilities. Dependency on speed changes needs to be explicitly modelled.
- The influences which active safety interventions might have on impact kinematics need to be analysed by full human body simulation and reflected in the method.

RESULTS. An outline assessment method was developed, consisting of five steps as listed below. Further development will include validation and calibration against real-world data, uncertainty assessment and possibly simplification for use by stakeholders such as Euro NCAP.

1. Active safety testing: Exposure / velocity curve shift. Driver warning and AEB systems will be assessed with respect to their ability to reduce impact velocity. Changes to impact kinematics due to this intervention will be noted for passive safety testing. Analysis of accident data will be used to define representative test scenarios.

2. Passive safety testing: Impactor measurement. Tests will be conducted to estimate impactor injury criteria measurements for the relevant vehicle speeds identified in Step 1.

3. Calculation of injury: Injury risk. Injury criteria measurements from Step 2 will be converted into an injury estimate for tested body regions using injury risk curves and velocity-exposure data from Step 1.

4. Calculation of cost: Socio-economic cost. Injury risks for tested body regions will be converted into costs.

5. Vehicle assessment: Weighting and summing. In the final step, costs will be weighted to account for non-tested body regions and ground impact. These costs will be summed to give an overall socio-economic cost for vehicles fitted with active and passive safety systems.

DISCUSSION and CONCLUSION. To complete the development of the assessment method, further substantial efforts are needed both to fill knowledge gaps and for validation.

3.2 Summary of Paper II

Assessment of Integrated Pedestrian Protection Systems with Autonomous Emergency Braking (AEB) and Passive Safety Components

AIM. This paper aims to develop and illustrate a benefit-based method for the assessment of integrated pedestrian protection as outlined in Paper I. This method was then used to estimate the benefits of cars with good, average, and poor Euro NCAP (passive safety) pedestrian ratings, in combination with a hypothetical A-pillar airbag and an AEB system.

METHODS. The integrated assessment method was developed to consist of 5 steps (Figure 4). The method was developed in two versions, one for Great Britain and one for Germany based on data from (and thus mainly applicable to) Great Britain and Germany, respectively. A Matlab code was created for convenient calculation of the integrated benefit using separate test data for active and passive safety technologies as input.

Step 1: Active Safety Testing: Exposure—Impact Velocity Curve Shift

Detailed and national accident data for Great Britain and Germany was used to develop baseline exposure—impact velocity curves appropriate for each country and to classify accidents into typical scenarios with their respective weight. Five test scenarios for laboratory tests of AEB systems, replicating relevant accident parameters, were developed by Seiniger *et al*. (2014) to which the accident scenarios were mapped. The mapping allowed for a proportional calculation, based on real world accident statistics and speed reductions measured with the AEB system in the test scenarios, of the shift in the exposure—velocity curve provided by the AEB system.

Step 2: Passive Safety Testing: Impactor Measurement and Extrapolation

Euro NCAP impactor injury criteria values at 40 km/h were extrapolated to other vehicle speeds using simple statistical functions from the literature (Searson *et al*., 2012a) or from simulations and tests performed by Rodarius *et al*. (2014).

Step 3: Calculation of Injury Frequency

Impact probabilities:

In the lateral direction the impact probability was assumed to be uniform over the car width for all impactors, which is supported by accident data. Longitudinal impact probabilities were only considered to be relevant for the headform impactor. A speed-dependent relationship between pedestrian height and the longitudinal head impact position measured as wrap-around distance (WAD) was established from results of simulations with the THUMS pedestrian human body model (Mottola *et al*., 2013).

WAD(log(v), Pedestrian_Height) =-2227+335log(v)+1.8Pedestrian_Height
where: WAD and Pedestrian_Height is in mm, and speed v in km/h

Injury risk:

Injury risk curves were taken from the literature.

- For the headform impactor, the injury risk curves used are from from Matsui *et al*. (2004) and are based on a logistic regression type called “Modified Maximum Likelihood Method” applied to pedestrian to car head impact data.
- For the upper legform impactor, the injury risk curve adopted for femur and pelvis injuries at AIS2 level is the average of the two risk curves based on logistic regression and a cumulative normal distribution developed by EEVC WG17 (2002).
- For the EEVC WG17 legform impactor, the injury risk curves used are from Matsui (2003) at AIS 2 level as it is assumed that these offer the best available data.
- For the Flexible Pedestrian Legform Impactor (Flex PLI), injury risk curves from Takahashi *et al*. (2012) were implemented.

Step 4: Calculation of Socio-Economic Cost

Injury frequencies for the body regions tested were converted into costs using a monetary measure of human and material crash harm (HARM) from Zaloshnja *et al*. (2004).

Step 5: Vehicle Assessment: Weighting and Summing

A body region calibration factor was used to correct the relative cost of injury for the tested body regions, i.e. head, upper leg and lower leg, as calculated for representative cars by the uncalibrated integrated assessment method. This body region calibration factor ensures that the calibrated integrated assessment method calculates injury cost of body regions matching the cost of those observed in accident data.

Subsequently, an overall calibration factor to correct the total cost of injury was calculated. This should help take into account injury to body regions not tested, injury caused by contacts with parts of the car not tested currently, and injury caused by ground impacts. This factor needs to align with an independently estimated AEB benefit reported in Edwards *et al*. (2014a) for a car representative of the average fleet in the accident data.

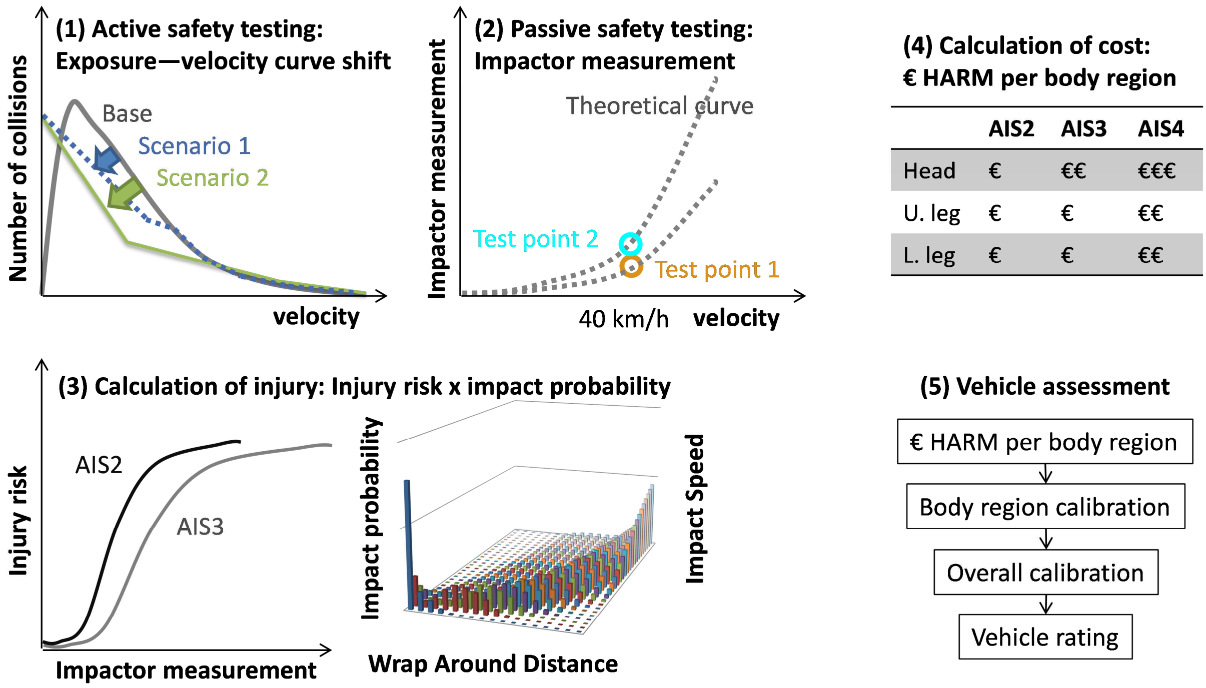


Figure 4. Integrated Pedestrian Safety Assessment in five steps

Four different configurations of active and passive safety were assessed (see Table 2).

- For passive safety impactor test data, test results representative of current good, average and poor performing vehicles with identical windscreen areas were assessed.
- For AEB input test data, one configuration with "No AEB system", i.e. zero impact speed reduction against the baseline exposure—impact velocity curves, and one configuration with "Current AEB system", i.e. speed reductions measured in Seinger *et al*. (2014), were assessed.
- To represent a hypothetical A-pillar airbag, impactor test results were modified on the A-pillars. This airbag was specified to activate between 21 km/h and 51 km/h, reducing HIC from 6000 to 400 at 40 km/h (Fredriksson and Rosén, 2014) and to follow the same HIC-velocity relation as for other vehicle structures (Step 2). Euro NCAP scores were estimated by changing the rating from red (zero score) to green (full score) for test points on the A-pillar.

RESULTS. Table 2 gives the assessment results for the German version of the assessment method for the following configurations: good, average and poor Euro NCAP passive safety rating with no system, with AEB system, with airbag, and with both AEB and airbag fitted. The percentages in brackets show costs normalised to average passive safety performance with neither AEB system nor airbag fitted. It should be noted that higher Euro NCAP scores indicate better protection, whereas, in the integrated assessment method, costs decrease with better protection.

Table 2. Pedestrian safety assessment results

Additional safety system	Passive Safety Level		
	Good	Average	Poor
Euro NCAP passive safety score rating			
No System	32.2 (142%)	22.6 (100%)	12.2 (54%)
A-pillar airbag	33.4 (148%)	24.4 (108%)	13.3 (59%)
Integrated method rating (million Euro)			
No system	662 (99%)	667 (100%)	943 (141%)
Representative current AEB	559 (84%)	563 (84%)	791 (119%)
A-pillar airbag	375 (56%)	338 (58%)	661 (99%)
AEB and A-pillar airbag	324 (49%)	333 (50%)	560 (84%)

DISCUSSION. The integrated assessment method predicts a significant positive impact on safety from the introduction of an A-pillar airbag, with a predicted reduction in casualty costs of 42-43% depending on passive safety level. The Euro NCAP method, in contrast, predicts a very limited safety benefit of only 5-8%. This difference can be attributed to the injury risk curves used and the procedure to calculate impact probability.

The injury risk curves for head injury show a substantial increase in risk for severe head injury at HIC values above 1800 and a large change from red (in tested areas, assumed to be HIC 1,800) to default red (for not-tested A-pillars, assumed to be HIC 6,000). Thus, A-pillar areas are substantially more important in the integrated assessment developed here compared to the Euro NCAP assessment.

Further, the integrated assessment method calculates the impact probability for the head for each WAD and divides this probability by the number of lateral test points for each individual WAD to calculate the impact probability for each test point. The highest WAD has only few test points because of the shape of the car and the marking out procedure. These few points are taken to be representative of the full width of the car and the windscreen area between these points, which would likely be default green, is not taken into account.

One should keep in mind that the hypothetical airbag was optimistically assumed to deploy in all collisions in the specified speed range. The AEB system was rather pessimistically assumed to give no benefit in some unclassified accident scenarios (20% of all cases) and not to affect exposure—impact velocity curves when the driver was already braking (60% of cases, but the benefit of AEB for partial and late braking was adjusted for in the calibration).

Further limitations of the assessment method include:

- An assumed linear relation between injury cost of tested and not tested body regions.
- The accuracy of the scaling of impactor criteria to impactor speeds and a disregard for any occurrence of bottoming out.
- The validity and accuracy of injury risk curves.
- The validity and accuracy of head WAD relationship with speed and pedestrian height.
- The validity and accuracy of using Euro NCAP assessment results for a single car to be representative of all cars in the accident data used for calibration.
- A disregard of the effects of vehicle pitching when braking.
- The mapping of test scenarios to accident scenarios.

CONCLUSION. A method to estimate the overall benefit of active and passive safety pedestrian protection was developed and successfully tested. The method utilises advanced integrated assessment in order to promote and spread best possible overall pedestrian protection and is ready for use in further assessments. It is encouraging that the method indicates benefits for safety systems of the same order of magnitude as predicted by previous research (Fredriksson and Rosén, 2012). However, limitations exist and it remains to be seen in retrospective accident studies whether the proposed method correlates better with observed injury outcome than other assessment schemes.

3.3 Summary of Paper III

Brake reactions of distracted drivers to pedestrian Forward Collision Warning systems

AIM. This study aims to quantify brake response time and brake behaviour (deceleration levels and jerk) to provide a detailed data set suitable for the design of assessment methods for pedestrian FCW systems.

METHODS. Distracted volunteers drove in a simulated urban environment in a moving-base driving simulator. In a surprise event, a simulated pedestrian crossed the road in front of the vehicle on a collision course with the vehicle. Drivers were warned of the imminent threat using four different settings of FCW systems. A control group received no warning.

RESULTS. Collisions and collisions avoided per setting are presented in Table 3a. Differences in collision rates were significant across settings (Fisher-Irwin exact test, $p<0.0001$). A brake pulse warning (Setting 2) was most effective in helping drivers avoid collisions; only one simulated collision occurred during this condition while 10 simulated collisions occurred for an audio-visual warning (Setting 1) and audio-visual warning with Head-up display (Setting 3). In terms of initiated braking (Table 3b), differences were significant across settings ($p=0.002$); however, only the brake pulse warning was significantly ($p=0.0005$) different from the control.

Table 3. Number of collision events and brake initiations prior to collision

		Setting 1 AV	Setting 2 BP	Setting 3 HUD	Setting 4 HUDfam	Setting 5 Control
a	Collision Yes	10	1	10	8	6
	Collision No	3	12	3	5	0
b	Brake initiation Yes	8	13	6	8	1
	Brake initiation No	5	0	7	5	5

Brake response times were, on average, shortest for the brake pulse warning (Setting 2, mean 0.8 s, SD 0.29 s) and longest for the control (Setting 5, mean 6.8 s, SD 2.8 s). Considering only the cases with brake response after the FCW and prior to collision, differences across Settings were not significant ($F=0.81$, $p=0.50$). Setting 2 (brake pulse) had the shortest response time as shown in Table 4, which is likely to contribute to effective collision avoidance.

Table 4. Brake response time for volunteers beginning to brake prior to collision

	Setting 1 AV	Setting 2 BP	Setting 3 HUD	Setting 4 HUDfam
Mean [s]	1.0 (N=8)	0.8 (N=13)	1.0 (N=6)	0.9 (N=8)
Standard Deviation [s]	0.43	0.29	0.59	0.39

Brake response (max. deceleration and jerk) was hardly affected by the FCW Setting, and does not seem to require modelling for each FCW system separately. A multivariate normal distribution and a linear regression were fitted to the pooled data from all four settings of maximum brake deceleration and jerk as shown in Figure 5. Blue circles are test values, a dashed line depicts the linear regression, and solid contour lines represent the cumulative normal distribution at the cumulative probability indicated on the line. Contour lines depict percentile values for brake response of the normal distribution, e.g. the “0.05 line” indicates that 5% of brake deceleration and jerk combinations are below and left of the line, and 95% of values above and right of the line. The linear regression line depicts representative combinations of brake jerk and brake deceleration. Combinations of brake deceleration and brake jerk, given a desired percentile value to be modelled, can be taken from Figure 5 as the intercept of regression line and contour line. For example, if a 10 percentile driver model is desired, values of 3.6m/s^2 deceleration and 5.3m/s^3 jerk can be read from Figure 5. For a 90 percentile model, values of 10.8 m/s^2 deceleration and 17.3 m/s^3 jerk can be taken.

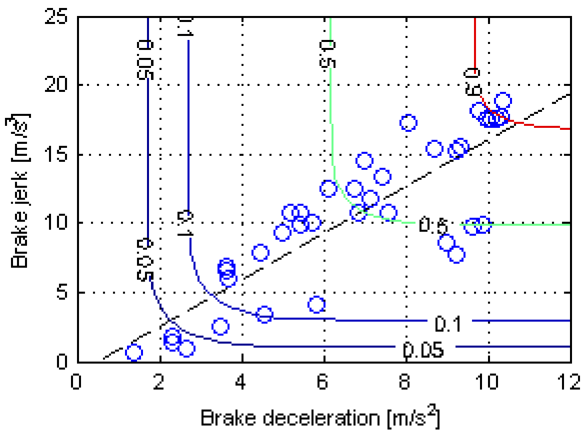


Figure 5. Brake deceleration and jerk model for FCW response.

DISCUSSION and CONCLUSION. Homma *et al.* (2014) report that 73% of drivers acknowledging notice of an audio-visual FCW for an imminent but unexpected car-to-car rear-end collision in a track test abandoned a secondary task. The remainder did not respond to the warning, which was attributed to a misjudgement of the urgency and warning content. These results are comparable to a reaction rate of 62% of the auditory-visual warnings in Setting 1, which may also include cases where the warning was not noticed at all.

The HUD in Settings 3 and 4 assisted drivers in locating the threat and inferring the type of threat. One might expect a shorter reaction time for the HUD compared to an audio-visual warning (Lees and Lee, 2008). In this study, however, no such benefit was observed. One can only speculate as to the reasons: The simulated imminent collision situation was simple to comprehend. A single pedestrian in strong contrast to the background crossed the street at a constant speed with no other moving traffic in the vicinity. It might be that the HUD did not improve the already quick recognition of the threat.

Driver models are needed for assessment schemes such as Euro NCAP's pedestrian AEB rating. In car-to-car AEB assessment, driver reaction to an FCW is modelled by a brake response time of 1.2 s and a maximum brake deceleration of 4 m/s^2 (Euro NCAP, 2015d). A similar driver reaction for pedestrian FCW might be modelled after data from this study as follows:

First, the proportion of drivers reacting at all and initiating braking could be modelled for each FCW system (Table 3) with brake response times for these drivers as presented in Table 4. Second, brake response in terms of jerk and maximum deceleration could be modelled based on the pooled volunteer response data, independent of FCW system, but correlated as presented in Figure 5. One only needs to select the percentile value of response relevant for the assessment scheme. Using the data from this study seems not only more relevant than using data from car-to-car collision experiments for pedestrian FCW assessment, but also enables the modelling of correlations and dependencies that could not be modelled using separate studies for each of the model parameters required.

Pedestrian crossing situations: Quantification of comfort boundaries to guide intervention timing

Drivers' comfort boundaries in pedestrian crossings: A study in driver braking characteristics as a function of pedestrian walking speed

AIM. These studies aim to quantify driver comfort boundaries, as indicated by brake onset, for the common scenario of a crossing pedestrian to provide practical thresholds for a False Positive assessment. As described in Section 1.5, if automated braking and warning systems activate before the comfort boundary is reached, this can be considered too early. Quantified comfort boundaries also provide a guide for system designers for appropriate activation timings irrespective of a False Positive assessment.

METHODS. Paper IV presents a test track study, while Paper V presents a simulator study. In the test-track study, 62 volunteers drove through an intersection once at 30 and once at 50 km/h; for the simulator study, 108 volunteers were driving at 30 km/h in an urban environment. In both studies, a simulated pedestrian was launched from behind an obstruction towards the driving path of the approaching car at 1 m/s and additionally, in the simulator study, at 2 m/s, per volunteer. In both studies, Time To Collision (TTC), longitudinal and lateral distance were measured at brake onset, and additionally, in the simulator study, brake deceleration and jerk were also quantified.

RESULTS. TTC was independent of driving speed but dependent on pedestrian speed. The 90-percentile value was 2.5 s TTC on the test track; in the equivalent simulator setting, with a 1 m/s pedestrian speed, the 90-percentile value was 2.6 s TTC which decreased to 2.2 s TTC for 2 m/s. Volunteers applied brakes at an average deceleration rate of 3.8 m/s^2 and a brake jerk of 3.7 m/s^3, and tended to brake harder with a later brake onset.

DISCUSSION. These studies successfully quantified driver comfort boundaries. Using, for example, 90-percentile values of brake onset TTC allows a differentiating threshold for too early a system activation to be set in the studies' pedestrian crossing situations. However, extrapolation to other test situations is not straightforward. Linear regression on the pooled test data for 1 m/s pedestrian speed depicted in Figure 6 indicates that no correlation between vehicle speed and TTC at brake onset exists. Brake deceleration and brake onset time are, to some extent, substitutable to come to a full stop as illustrated by the lines of necessary brake onset at different deceleration levels in Figure 6. Drivers seem to be somewhat more likely to adjust brake deceleration than brake onset for pedestrian encounters in urban environments. At higher instructed initial speeds, drivers might reduce initial speed against instruction where there is restricted visibility, might choose to start braking much earlier where there is early visibility of the pedestrian, might expect the pedestrian to take evasive action and not react at all, or might attempt avoidance by steering. Further influencing factors, for example light and road conditions, may exist.

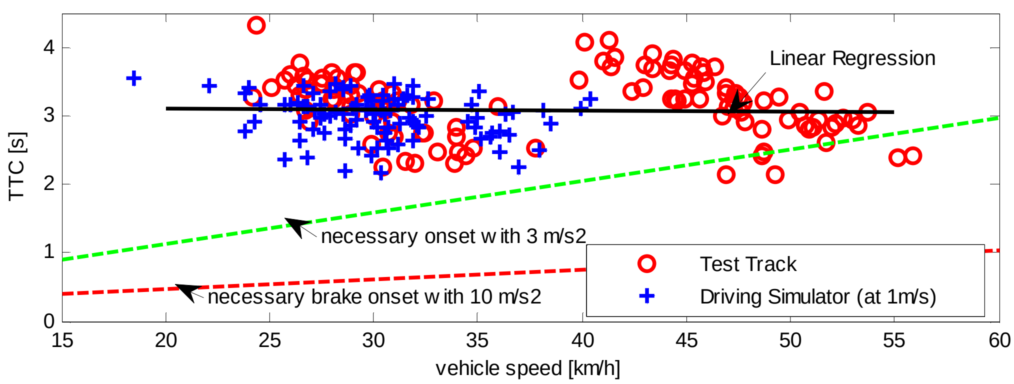


Figure 6. TTC at brake onset and initial vehicle speed

Brake onset was measured as the indicator for comfort boundaries. This indicator was chosen as "the most intuitive reaction of a driver to a pedestrian-related dynamic hazard is to push the brake pedal" Bromberg *et al*. (2012). TTC at brake onset was chosen as TTC appears to be the most widely adopted FCW evaluation metric (Montgomery *et al*., 2014) and seems therefore most suitable for False Positive assessment. TTC is also less affected by driving speed and shows a narrower spread than longitudinal and lateral distances. However, no proof was presented that brake onset TTC is an accurate measure for driver comfort coundaries. Further studies should relate brake onset TTC with direct measures of driver stress levels or subjective self-reported assessments of stess levels or desirability of different system intervention times.

CONCLUSION. Driver comfort boundaries in pedestrian crossing situations were quantified. Selected percentile values from the collected data can be used to design False Positive test thresholds. These tests could replicate the True Positive test situations, and thus require little additional testing. System activation before comfort boundary in these tests would be deemed too early. Careful extrapolation of these thresholds to other test situations in current True Positive performance assessments would allow a simple and practical test to discourage too early, and thereby annoying, system activation. Furthermore, system designers might use comfort boundary distributions as guidance for development, irrespective of False Positive assessment.

3.5 Summary of Paper VI

Assessment of Integrated Pedestrian Protection Systems with Forward Collision Warning and Automated Emergency Braking

AIM. This paper aims to develop an integrated pedestrian safety assessment method that includes AEB and FCW systems. The paper also aims to evaluate the benefits of FCW systems with the developed method.

METHODS. The German version of the integrated pedestrian safety assessment method (Paper II) was extended to quantify the benefit of AEB and FCW systems in terms of casualty cost reduction for a generic vehicle with an assumed good Euro NCAP passive safety score.

A driver model based on a Driving Simulator study (Paper III) was added to the integrated assessment method from Paper II. This allows an estimation of the speed reductions achievable with FCW and subsequent driver-initiated braking.

The performance of AEB and FCW systems were assumed to activate at two different timings: Firstly, late activation when a pedestrian approaching the driving corridor of a vehicle can no longer avoid entering it due to the pedestrian's limited ability to instantaneously change direction ('green zone' in Seiniger *et al*., 2014) and secondly, early activation at the time of crossing the driver comfort boundaries (Papers IV and V). The performance of the FCW systems was also quantified for two different warning interfaces. In total six systems were studied: AEB, FCW audio-visual, and FCW brake pulse, each in early and late activation.

RESULTS. Costs for the six systems normalized with no system are given in Figure 7: the lower the cost, the higher the benefit. Both early and late AEB systems were assessed as giving a benefit of around 25%. Late FCW systems offer little or no benefit, whereas the benefit gained from early FCW systems is dependent on system type: the early FCW system with brake pulse was assessed as giving a reduction of 25%, but the audio-visual FCW system offered rather less at 16%. These results indicate that an FCW system can be as effective as an AEB system for pedestrian protection, but that this effect is dependent on FCW system design.

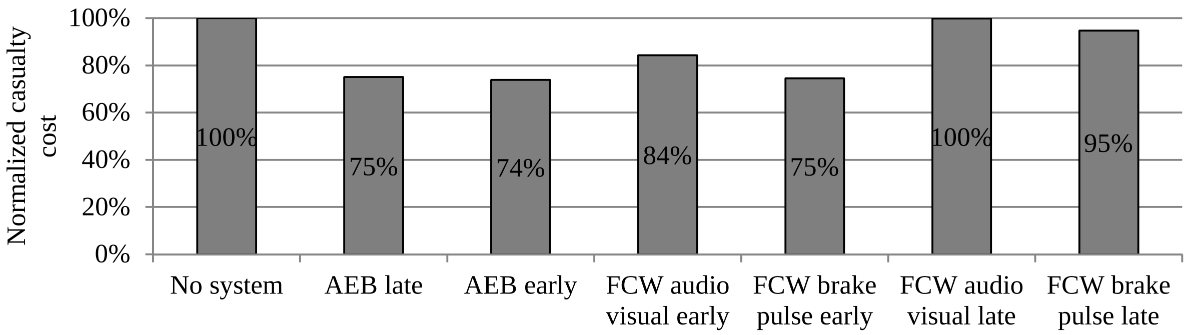


Figure 7. Normalized casualty cost of AEB and FCW systems

DISCUSSION and CONCLUSION. This paper quantified the benefit for two different activation times of AEB and two FCW systems. These are not the only possible activation times; the selection was made to represent a somewhat typical late activation, which is thought to reduce False Positive activation (Seiniger *et al*., 2013).

However, not all False Positive activations necessarily lead to driver dissatisfaction (Källhammer, 2014). This led to the definition of early system activation at driver comfort boundaries measured in experiments with attentive drivers (Papers IV and V).

In the light of the high potential of FCW systems found in this study, it seems necessary to include FCW performance tests in the assessment of pedestrian protection. The implementation has been demonstrated in this paper. Speed reductions in the test scenarios have to be measured, which requires modelling of driver reaction to a warning. Such reaction models could use values reported from the experiment in Paper III.

4 General discussion

A method to assess combinations of passive and active safety offered by cars has been developed. Airbags were identified as an effective means to improve safety while AEB and FCW systems showed important but lower levels of effectiveness. FCW systems were shown, based on the data collected, to have the potential to be as effective as AEB systems. This provides new evidence that a discussion of FCW systems for pedestrians is warranted, and counters the commonly-held opinion that warnings would be too late to be effective.

In Section 4.1 below, the integrated assessment method proposed here is compared to existing practices, which are reviewed. Section 4.2 discusses the methods applied in the papers while Section 4.3 discusses the applicability of the proposed False Positive thresholds for different active safety systems. Section 4.4 expands on the limitations of the assessment method proposed. Section 4.5 outlines the implications for practice in the assessment of the expected impact on safety technologies, and finally Section 4.6 identifies some of the future research needs for integrated pedestrian safety assessment.

4.1 Comparison to existing theories and methods

Key features of the integrated assessment method developed (Papers II and VI) are compared to other proposals in Table 5.

Table 5. Key features of integrated assessment methods

	VERPS	Searson *et al*. method	PreEffect-iFGS	This thesis
Body regions considered	Head and lower leg	Head only	Head, upper and lower leg	All (Tested as Euro NCAP, linear weighting of others)
Weighting	No weighting, separate assessment	No weighting (head only)	Head: 67% upper leg: 17% lower leg: 17%	Real-world injury cost distribution
Injury risk reduction	Injury probability as function of impact speed	Injury probability as function of impact speed	Calculated with injury-shift method	Injury probability as function of impact speed
Impact speed	40 km/h	Real-world impact distribution	40 km/h	Real-world impact distribution
Effectiveness measure	Risk reduction at AIS3+ level	Unspecific cost function, example of risk reduction at AIS3+ and AIS6 level	Risk reduction at MAIS2+ level	Total casualty cost
Impact point probabilities	Real-world: Vehicle specific by simulation	Uniform over test area	Uniform over test area	Real-world by simulation
References	Kühn *et al*., 2005 Kühn *et al*., 2007 Hamacher *et al*. (2011) Hamacher *et al*. (2013)	Anderson *et al*., 2012b Hutchinson *et al*., 2012 Searson *et al*., 2010 Searson *et al*., 2012a Searson *et al*., 2012b Searson *et al*., 2014	Schramm (2011) Roth and Stoll (2011)	Papers II and VI

Some features of the assessment method proposed in this thesis are comparable with the Searson *et al*. method: Both methods reflect real-world impact speed distribution and evaluate injury reductions using injury probability and related cost modelled as a function of impact speed. These features have several potential advantages. Using cost, pedestrian protection is calculated in a single indicator, which allows a direct comparison between different vehicles and safety concepts, and makes the assessment more comprehensible. Assessing injuries at all severities rewards all safety improvements. The reflection of actual real-world impact speeds contributes to avoiding sub-optimisation to a single (potentially irrelevant) impact speed and contributes to making the assessment more realistic.

Contrary to previously developed integrated assessments (Table 5), it is here seen as necessary to consider all body regions of the pedestrian in the assessment, and to weight them according to real-world injury occurrence. If only head injuries are considered, for example, a majority of injuries are not addressed (Figure 2). Addressing some of the other injuries is difficult, because only a limited number of body regions are represented by impactors. For example, an impactor representative of the pedestrian chest is currently unavailable, and therefore chest injury prediction is not currently possible. Approximation methods, such as relating chest injury to HIC measured by the established head impactor (Han *et al*., 2012) have been used in the past. The method in this thesis proposes the calibration of total injury cost calculated (based on limited body regions) against an independent estimate of such cost (based on all injuries), and thereby relates the injury cost of non-tested body regions linearly to those that are tested.

In line with the VERPS method, the impact area and dependency of impact probabilities on impact speed are explicitly modelled. This is important as the shift of impact location with reduced speed might in some cases increase injury probability (Matsui *et al*., 2011; Watanabe *et al*., 2012) and with a fixed impact area and impact probability, such effects cannot be replicated. Both VERPS and the method developed in this thesis obtain impact probabilities and predicted WAD from simulation using a pedestrian human body model. While VERPS relies on multibody simulations using models provided by MADYMO, the method proposed in this thesis makes use of simulations using the FE-model THUMS that were carried out by Mottola *et al*. (2013).

VERPS prescribes the classification of vehicles under assessment into categories by geometry and uses category-specific impact kinematics; this thesis prescribes only one function of relating impact speed with impact probability. While vehicle geometry and stiffness undoubtedly will influence impact kinematics, it was seen as difficult to accurately categorise all vehicles under assessment. The limited increase in accuracy of a purely geometry-based classification (neglecting the influence of stiffness) might not justify the vast increase in effort.

VERPS uses pedestrian height distributions from accident data; separate assessments for children and adults are included, while the method in this thesis uses data from the general population and gives one combined assessment. Another difference concerns areas on the vehicle front not assessed by Euro NCAP: VERPS assumes generic values (e.g. HIC 999 for windscreen and HIC 2000 for the roof) while the method proposed in this thesis makes use only of data from impact points that are actually assessed using impactors, effectively ignoring impacts outside the assessed area. The sensitivity of the resulting casualty costs to this assumption is presented in Appendix 1. This assumption influences results; nevertheless, A-pillars are identified as the major contributor to casualty cost for all assumptions.

One of the implications of the method proposed in this thesis is that pedestrian airbags are an effective means of reducing pedestrian casualty cost. This implication aligns with previous research highlighting head to windscreen frame impacts as major contributor to pedestrian injuries (Fredriksson *et al*., 2010) and cyclist injuries (Katsuhara *et al*., 2014). About 50% of pedestrian head injuries were sustained at WAD above 2000 (Kiuchi *et al*., 2014), which is where the A-pillar is located for most vehicles. Fredriksson and Rosén (2012) calculated that pedestrian airbags had an effectiveness of 34% in preventing AIS3+ head injuries, and AEB systems an effectiveness of 44%. Hamacher *et al*. (2013) assessed windscreen airbags combined with an active bonnet and AEB system for six categories of passenger cars. For four of these vehicles, a windscreen airbag combined with an active bonnet was more effective in preventing pedestrian head injuries than an AEB system, although the difference was small. Thus, the high effectiveness of pedestrian airbags as calculated in Paper II appears to be well aligned with current knowledge and practice.

4.2 Methodological reflections

A variety of methods were employed to develop the integrated pedestrian safety assessment method (Paper II) and its extension to FCW assessment (Paper VI). Choices between available methods had to be made throughout the studies; some choices were clear while others were less obvious with several possible options. Some considerations on methodological choices are debated below.

Test scenarios are used to measure speed reductions of active safety systems (AEB and FCW) on a test track (Figure 4, step 1). The choice was made to base the weighting of these test scenarios on the number of fatally and severely injured pedestrians in past accident data. However, this historical data might not accurately describe the future or even the present situation of pedestrian collisions as driver and pedestrian behaviour, the environment and vehicle technology change with time, and influence either immediately or with a delay collision occurrence patterns and their injury outcomes. Methods to predict the influence of such changes and the population and characteristics of collisions which result have been developed (Strandroth *et al*., 2012; Anderson and Searson, 2014) and could be an alternative basis for the weighting of accident scenarios. Simply, assuming assessment of AEB and FCW systems in the year 2016, one could weight test scenarios against the collisions predicted to occur in 2016 instead of the collisions which occurred in the past as recorded in accident data. However, the prediction of such changes and their influences on pedestrian collisions is not easy given the uncertainties and a general lack of data, and can be criticized as being (at least to some extent) subjective in the underlying assumptions of the effects that safety features would have in single, concrete, incompletely documented, accidents. To avoid speculation on intended subjectivity, it was seen as beneficial to use objective – but likely flawed – historical accident data over more relevant – but likely subjective – forecasted residual populations of accidents.

Probabilities of head impact in the longitudinal direction are dependent on vehicle speed and pedestrian height. These probabilities are used to weight impact points in the head test area: An impact point that is more likely to be hit has a larger contribution to pedestrian safety. These probabilities were developed based on FE simulations with THUMS version 4 (Mottola *et al*., 2013). An alternative to simulation methods (Mottola *et al*., 2013; Hamacher *et al*., 2013; Peng *et al*., 2011) could be the use of mathematical relations between parameters of the accident and longitudinal impact point as recorded in accident databases (e.g. Fredriksson and Rosén, 2012; Kiuchi *et al*., 2014). While the trend that higher speed and taller pedestrians impact at larger longitudinal distances is consistent across studies and methods, the magnitude of the influence differs somewhat depending on car model, simulation and reconstruction method, and region. Accuracy and control for confounders appears to be better when utilizing simulation methods under the precondition that the pedestrian and vehicle models are validated.

THUMS version 4 has been validated to reproduce pedestrian accidents kinematics and injuries (Shigeta *et al*., 2009; Watanabe *et al*., 2011; Watanabe *et al*., 2012). THUMS has been used for research into injury mechanisms in accidents (Watanabe *et al*., 2012) and for the development of vehicles for real-world safety (Yasuki, 2006). THUMS WAD was compared to PMHS pedestrian impact tests at 40 km/h conducted by Kerrigan *et al*. (2007) and Kerrigan *et al*. (2009). Analysing this comparison, Mottola *et al*. (2013) found that, excluding the "large SUV" cases, the head WAD from the PMHS of AM50 stature falls in the corridor predicted by THUMS simulations.

Current **injury criteria** were utilized to ensure that the active and passive safety assessment methodology was based on current best practice. A review of injury criteria for pedestrian impactor testing was conducted by Lawrence *et al*. (2006) and Bovenkerk *et al*. (2008). These current injury criteria are not free of criticism, and new ones might be beneficial or even required. For example, the injury risk for the head is assessed with HIC, a time-bound measure of linear acceleration. Originally developed for skull fractures, HIC has some relation to rotational acceleration and brain injury. However, the need for a head injury criterion based on rotation has been emphasized in many studies (e.g. Takhounts, 2015). If new injury criteria were to become best practice in pedestrian passive safety assessment, it would be necessary to revise the method and implement them. As the logic and structure of the integrated assessment would remain intact, such a revision should be possible.

Injury risk curves to relate impactor measurements to the probability of injury at different severities were taken from literature, and are therefore established knowledge (Figure 4, step 3). Since the method proposed in this thesis is intended to be applicable to consumer and regulatory testing, it focuses on the assessment of passive safety using subsystem hardware impactors and established injury criteria. However, several risk curves were available to choose from for existing injury criteria and one could also consider modifying published analysis methods to construct a new set of curves. While the integrated assessment method aimed at including all AIS levels, effectively these were only adopted for head injuries as only AIS2+ injury risk curves were available for leg injuries. For head injuries, alternatives appeared to be a set of risk curves by Matsui (2004) and a set developed by NHTSA (1995) as discussed in Edwards *et al*. (2014b).

Matsui (2004) developed pedestrian headform injury risk curves based on the reconstruction of real-world pedestrian accidents. By the nature of accident reconstruction, for these injury risk curves an implicit transfer function from human to impact device is included. Injury probability is given for all AIS levels using a logistic regression type called "Modified Maximum Likelihood Method" (MMLM). This method adds a constraint to the logistic regression, namely that the injury risk needs to be zero at zero stimulus (Nakahira *et al*., 2000), and has been subsequently criticized (Banglmaier *et al*., 2002; Bovenkerk *et al*., 2008). Consequently, one may consider modifying the analysis to use the more common unconstrained or standard logistic regression. Upon doing so, Edwards *et al*. (2014b) noted that HIC values at 50% injury probability for all AIS levels are about the same for either method as the curves cross. MMLM gives a lower injury probability at any HIC value below the crossing point due to the constraint to give zero response at zero stimulus. As logistic regression curves are always symmetric, this leads necessarily to MMLM giving a higher injury probability at any HIC value above the crossing point. MMLM curves appear to be the more plausible of the two sets.

In addition, it can be extremely difficult to reconstruct an accident and get correct pedestrian kinematics if actual films of the accidents are not available: The car speed, pedestrian stance, direction etc. need to be estimated. Errors can be very large. The exact procedure is described in Japanese only, thus it is difficult to assess the quality of the reconstructions. It can be noted that Matsui (2004) verified the reconstruction of accidents by a comparison of dent depths. A similar procedure has also been used for the construction of upper legform injury risk by Rodmell and Lawrence (1998). Thus, some limited validation of the reconstruction data has been carried out to increase the validity of the injury risk curves.

Further, it should be noted that Matsui (2004) measured HIC_{36} when HIC_{15} is commonly used for pedestrian testing nowadays, and used a 2.5 kg child headform impactor while one of 3.5 kg is currently used in regulatory and NCAP testing. The effect of changing the mass can vary: Structures might bend under loading with a 3.5 kg impactor and not bend under loading with a 2.5 kg impactor, resulting in increased HIC values. Where bottoming out occurs with a 3.5 kg impactor, it might no longer occur with a 2.5 kg impactor, reducing HIC values.

Schmitt *et al*. (2004) note that the PHMS data used to establish human injury risk curves by Hertz (1993) "consists of short duration impacts of typically less than 12 milliseconds, the curve is applicable to both HIC_{15} and HIC_{36}". Assuming that the pedestrian headform reconstructions were carried out impacting hard structures, one can in turn assume a short impact duration; consequently, the curves developed for HIC_{36} would be identical with those for HIC_{15}.

Non-pedestrian injury risk curves have been developed by NHTSA (1995). These were based on skull fracture injury risk curves from Prasad and Mertz (1985) who constructed curves from PMHS drop test data. Other AIS levels were constructed using two different approaches: "expanded Prasad/Mertz" and "Lognormal" curves (NHTSA, 1995). "*These 'expanded Prasad/Mertz' curves were derived by extending the relationship between the MAIS 3 and MAIS 4 curves developed from the Thoracic Trauma Index (TTI) (used to measure impact severity to the chest in side impacts) to the MAIS 4 HIC curve representing brain injury"* (NHTSA, 1995). Thus these "expanded Prasad/Mertz" curves appear to be questionable and an approximation at best.

“Lognormal” curves were derived using the following procedure (NHTSA, 1995)

1. Prasad and Mertz (1985) data was treated as censored and described as lognormal distribution
2. Skull fracture was assumed to give MAIS2+ injury
3. Data from NASS and CDS was treated as censored and used to relate car velocity change to car occupant head injury
4. A relation between velocity change and injury outcome was described as lognormal distribution
5. A function to relate velocity change to HIC was established based on the available MAIS2+ data
6. Head injury risk curves for specific injury level or higher were described as lognormal distribution.

The “lognormal” injury risk curves include reconstructions (step 3), but it may be easier to reconstruct car occupant accidents than pedestrian accidents. Further, cadaver test data was used as a basis (step 1) while Matsui (2004) used reconstructions only. The applicability to pedestrian impact conditions of the relation between velocity change and HIC derived from MAIS2+ car occupant head injuries is of importance for the validity of these curves. This additional step of relating head injury to HIC via velocity change might introduce an additional error compared to the direct relation of HIC and injury carried out by Matsui (2004). Further, these injury risk curves are developed for humans; a transfer function to the pedestrian headform is not available or alternatively, proof of biofidelity has not been provided.

The assessment method proposed uses the Matsui (2004) MMLM injury risk curves in spite of relevant criticism as the use of pedestrian to car head impact data is seen as having greater relevance than data on head to car interior impacts.

Another consideration for injury risk curves is whether the data used for injury risk curve construction represents the population at risk of pedestrian collisions. Often, the biomechanical data is obtained from PMHS tests or accident reconstructions, and are biased towards elderly males. Thus, such risk curves might not lead to optimal solutions for the younger population and females, as their injury risk differs from elderly males. There seems to be a need for the continued collection of raw biomechanical data to accurately incorporate the effects of age and gender into pedestrian injury risk curves.

Virtual testing was not utilized in the assessment method but could be used to assess the passive safety and active safety performance of a car. It is proposed instead that passive safety tests are carried out with hardware impactors and active safety with hardware targets on a test track. This is based on a consideration of today’s state-of-art and the intention to develop a ready-to-use method. The availability and validation of virtual models might still be incomplete, one reason not to propose the widespread use of these models in assessments. Another issue is the impossibility of validation of all models by an assessment body, although this might be resolved by reducing the role of an assessment body to the verification of a few results provided by the manufacturer, making use of proprietary, confidential virtual models. The verification could then be done using the classic hardware settings with a reduced number of tests.

Comfort boundaries were measured and quantified experimentally. The experiments were carried out on a **test track** (Paper IV) and using a **driving simulator** (Paper V). It is always questionable whether such “laboratory experiments” accurately represent “real-world” situations and are applicable outside the laboratory. Efforts were undertaken to replicate “real-world” situations, and similar results were obtained independently in the track study and in the driving simulator study. These results are encouraging, but are, nevertheless, results of experiments. Repeatability and control of the experimental condition was considered very important in this thesis. **Naturalistic Driving Studies**, having excellent face validity, were not conducted, since the time needed to collect a similar amount of data would have far exceeded that which was available. It would be valuable to conduct such Naturalistic Driving Studies not only to confirm the laboratory experiments, but also to develop driver individual comfort boundaries. Such boundaries will predict drivers’ “natural” brake timing for a given conflict situation deduced from driver characteristics such as age and gender (as done for car-to-car conflicts by Montgomery *et al*., 2014) or deduced from historical braking behaviour (carried out for car-to-car conflicts by Aoki and Osaki, 2013).

Assessments of vehicle pedestrian protection needs **metrics to assess the benefit or protection offered**.

The use of a single injury severity level is appropriate when the aim is to eliminate injuries above this severity level altogether. For the goal of eliminating all severe to fatal injuries, a certain single collision outcome is a failure regardless of whether it contains single or multiple severe or fatal injuries. Most assessment methods are based on predicting injury risk at one selected AIS level.

The implications of choosing one AIS level are illustrated for the risk of head injury using injury risk curves developed by Matsui (2004). As Figure 8 (top) shows, the probability of injury increases with increasing HIC values. Lower injury severities occur already at lower HIC values. Figure 8 (bottom) depicts the HIC range covered from 10- to 90-percent risk of the same injury risk curves. This range indicates where changes in HIC have large influence on injury risk. One can see that AIS2+ injury risk changes mainly between HIC 600 and 1100, while for AIS5+, injury risk changes mainly between HIC 2100 and 3900. In consequence, using AIS2+ as metric for head injuries will encourage vehicle designs that achieve HIC values of 600. There is little measured benefit in achieving HIC values below 600 and there is little measured benefit of trying to reduce high HIC values if the attempt does not result in values below 1100. Using AIS5+ as a metric, these borders and thereby encourages vehicle design are different. Searson *et al*. (2014) note that disregarding improvements outside the borders of the chosen AIS level needs careful consideration as “there may be merit in rewarding any improvement in safety; conversely, it may be thought that once risk rises to a certain threshold, no credit should be given.”

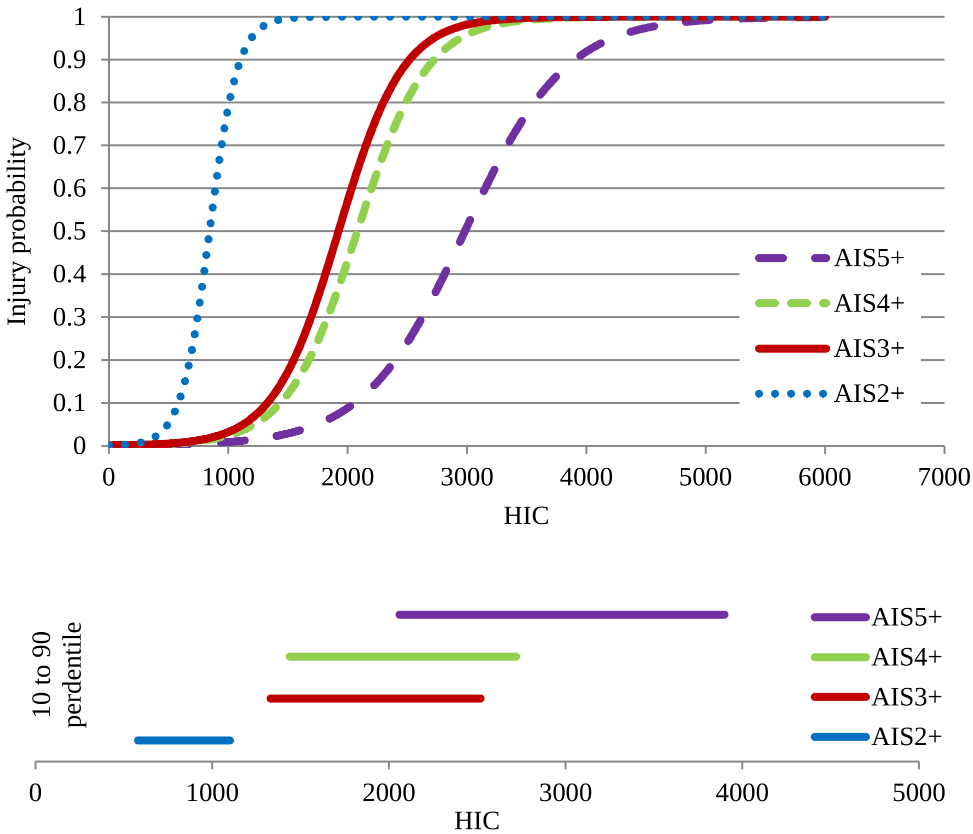


Figure 8. Head injury risk curve from Matsui (2004). Top: Cumulative Risk. Bottom: HIC values for 10 to 90 percentile risk at different AIS levels

Choosing one AIS level as the basis for a safety performance metric can be avoided by reporting the performance at several levels. However, humans are known to fail at making rational choices when faced with alternatives differing in consequence and likelihood (Burgman, 2005; Kahneman, 2011). The recent introduction of overall safety performance in most NCAPs (combining previously separate assessments) might be seen as evidence that a single aggregate measure is beneficial over the reporting of several performances. Euro NCAP attributes its success to a growing community accepting star ratings which are easy and accessible as legitimate indicators of safety performance (van Ratingen *et al*., 2011). The use of an aggregate metric, or an overall performance indicator, such as HARM or rpmi might be beneficial over reporting several indicators.

HARM describes injury cost values derived from US vehicle occupants (Zaloshnja *et al*., 2004). Cost values for European pedestrian injuries might differ because medical treatment and injury types differ. The calculations by the author using GIDAS data showed that, while injury types for a given body region and severity level differed between car occupants and pedestrians in Germany, the length of hospitalization as an indicator for cost did not. Furthermore, for a relative assessment, only relative differences are important, and these could be sufficiently small.

As with HARM, it is questionable whether rpmi values are directly applicable and could have been used as an overall performance indicator in the integrated method. Car occupants and pedestrians might have different injuries with a different rpmi for a given body region and severity level. These different injuries might lead to a different rpmi when averaging for a specific body region and severity level. The influence of a different injury spectrum was confirmed using the Swedish Traffic Accident Data Acquisition (STRADA) data (16989 injuries for occupants and 8725 injuries for pedestrians). Resulting differences in the rpmi between Swedish car occupants and pedestrian injuries were small except for AIS4 chest injuries, where occupants had an rpmi of 15% while pedestrians had an rpmi of 100%. Overall, the application of the rpmi metric, developed for car occupants, to pedestrian injuries appears reasonably accurate.

For the assessment method proposed, HARM was selected as an overall performance indicator, as it seemed reasonably accurate and simple to use.

4.3 Comfort boundaries as a guide to activation time (theoretical reflection)

Comfort boundaries are proposed as False Positive test thresholds. This section discusses whether comfort boundaries are equally applicable to warning and automated braking systems and is based on a framework for active safety evaluation developed by Ljung Aust and Engström (2011).

This framework makes use of two boundaries: Firstly, a safety boundary, which divides states of maintained control and loss of control beyond recovery and secondly, a comfort boundary, dividing states of a feeling of discomfort to the driver and a feeling of comfort. Drivers aim at a state within the comfort zone and take corrective action when they exceed the boundary.

It is necessary to provide the warning before the safety boundary is reached to ensure control is retained: A warning at the time of losing control will, given that a human driver always requires some time to react to a warning, inevitably result in a loss of control. Most active safety warning systems are designed with the aim of avoiding collisions, not only mitigating them. Thus, warning before the safety boundary is crossed is essential.

For automatic braking, there is generally no relation between driver trust and system performance when the system is operating. However, if annoyed by system activations, the driver might want to switch the safety system off altogether thereby eliminating safety system performance completely. Furthermore, a driver might not opt for the technology again given the choice at the next car purchase or rental. Thus, automatic braking systems need to be designed and assessed with consideration to driver trust. These systems could be activated before the safety boundary is crossed to meet driver expectation, since it is possible to imagine situations where a driver would have expected automatic braking despite the fact that the oncoming conflict, without activation, would not evolve into a collision. It seems to be plausible to assume that within the comfort boundary, automatic braking would be considered a nuisance in the same way as a warning, perhaps more so. Thus, as for warnings, automatic braking should not occur before the comfort boundary is crossed. However, while warnings should take place at the comfort boundary for system performance reasons, automatic braking could take place somewhere between the comfort boundary and the safety boundary. Further empirical data is needed to relate the exact timing of automatic braking to the desirability of the True Negative event of automatic braking.

It might also be the case that, being aware of their distraction, drivers would appreciate an even earlier warning than the at attentive comfort boundary since raising attention levels and orientation for the distracted driver take time. To verify this hypothesis a different type of analysis is needed: Subjective driver responses on the desirability of issued warnings for various activation times need to be collected. This will necessarily raise issues of objectifying subjective responses.

The comfort boundary is likely to differ among individuals and circumstances. Driver personality and ability, as well as road and vehicle conditions and the traffic situation under consideration, are likely to be influential. The selection of appropriate percentile values of a population (e.g. below 90% of drivers' threshold) may be suitable for determining current system design and assessment while driver adaptive solutions may be applied in the future. For these solutions, a False Positive test should not be conducted against a fixed threshold, but the threshold should be determined from the driver type and condition suitable for the test situation. It might be necessary to conduct different tests, and have different thresholds, for example for attentive and sleepy drivers.

In summary, current knowledge therefore suggests that neither warnings nor automatic braking should be activated prior to the comfort boundary of an attentive driver. Whether drivers identified as distracted would appreciate an earlier warning remains to be proven. Thus, the definition of comfort boundaries from empirical data is highly relevant for the assessment of active safety systems that either warn the driver or brake automatically. If the comfort boundaries of a particular test situation, either for an individual driver and an adaptive system, or for a certain percentile value of the driver population, are known, assessments could penalise activation occurring before this threshold has been reached. Using such a False Positive test leads to a higher overall safety performance by increasing True Positive performance through earlier activation only within reasonable boundaries, and thus avoids detrimental effects on safety via driver mistrust.

4.4 Limitations

The proposed method is ready to be used, but has its limitations as already discussed in the summary of the papers and the section on methodological reflections in detail. In the following some additional general limitations are emphasized.

The method assesses passive safety as the ability of the frontal structures of a vehicle likely to be impacted by a pedestrian to mitigate injury outcome (thereby, for example, excluding reversing and run-over injuries). It also assesses active safety as the ability of systems to reduce speed prior to a collision, including automated braking systems (AEB) as well as systems warning the driver of an imminent collision and achieving speed reduction by means of driver initiated braking (possibly with brake assistance). Beyond the scope of this thesis are, for example, systems that aim to reduce the number and severity of collisions by supporting the driver when no collision is imminent, such as fatigue monitoring or night vision enhancement. Systems also exist which aim to avoid collision by means other than speed reduction, such as those employing automatic steer avoidance to steer around a potential collision partner (Toyota, 2013); these also fall beyond the scope of this thesis. Speed reduction and other technologies seem to be fundamentally different, as speed reduction is likely to mitigate injury outcome even if the collision cannot be avoided altogether (even though the possibility of changing impact location and increasing probability of injury exists) while the mitigation potential of, for example, "partial" steer avoidance, that is, steering but not avoiding a collision, is less obvious.

The method proposed relies on the testing of active safety systems in representative scenarios, and on the testing of passive safety with impactor tests. Thus, any limitations of the test procedures for active and passive safety, such as unrealistic reflectivity of test targets or lack of biofideltiy of impactors, will have its impact on the method. In the future virtual testing could turn out to be more powerful than hardware testing concerning biofidelity or availability of body regions. Then, virtual testing could replace hardware testing.

The method currently does not quantify uncertainty. A thorough quantification of uncertainty is desirable to be able to determine confidence intervals for the calculated best estimate of benefit of any combination of systems. For some elements, such quantification would be straightforward, but for others nearly impossible. For example, it would be very difficult to determine the accuracy of the mapping of test to accident scenarios, which was therefore not attempted in this thesis even though it would clearly be beneficial for interpretation of the results provided by the integrated method.

The need to separate active and passive testing may be overcome in the future. The whole chain of events could be tested or simulated in one run: The hardware sensor target for active safety evaluation might simultaneously be a suitable hardware impactor for passive safety assessment. Also, simulations might be established for active and passive safety features simultaneously. Such a method might replicate system interaction in an integrated method more directly and better than the method proposed, which relies on separated hardware testing for integrated assessment.

Comfort boundaries were quantified to provide a False Positive assessment, but limitations include the fact that only two influencing factors were incorporated and the general lack of verification of technology—comfort boundary relationships. The influence of two driving and pedestrian speeds on comfort boundaries were quantified (Papers IV and V). These factors were believed to be of major importance and are commonly varied in the assessment of True Positive system performance assessment. However, the list of other potentially influencing factors is long: The time of day, road type, priority rules, driver mood and driving skills, road surface and available or estimated friction, crossing angle, pedestrian size and age, and eye contact or other types of communication are just a few. Rightfully, one might argue that the work presented misses potentially influencing factors, and only quantifies comfort boundaries to some extent. Thresholds for False Positive testing might need to be adjusted if these influencing factors were to be included in the assessment.

Fundamentally, driver acceptance of system intervention when comfort boundaries were passed remains a hypothesis, even if a plausible one. Further research is needed to verify through more subjective and qualitative experimentation the relation between comfort boundaries and technology acceptance.

In summary, two assessments are proposed: One for True Positive performance, the integrated assessment method, and another, separate one for False Positive performance which sets limits to acceptable activation time to ensure best overall results for pedestrian protection. While the True Positive assessment procedure is detailed and quantitative, the False Positive procedures might require further investigation into influencing factors. Consideration should also be given to the possibility of combining True Positive (casualty cost reduction) performance and False Positive (Driver annoyance reduction) performance into a single metric, such as Number Needed to Treat (NNT) which describes the number of necessary system actions per correct system action. Helmer (2014) suggests that, for a simulation approach to determine the effectiveness of active safety systems, NNT combined with the consequences of False Positives can be used to calculate a trade-off between False Positive activation and driver annoyance, on the one hand, and true positive system performance on the other hand to achieve the best overall safety effects.

4.5 Implications and contribution to practice

This thesis aims at developing the means to assess the integrated pedestrian protection offered by passenger cars (Papers I, II and VI) which will allow the prioritizing of countermeasures and avoidance of sub-optimisation of passive or active systems that can occur when designing and assessing these systems in isolation. Further, it aims to reduce pedestrian causalities by enabling a better understanding of driver comfort boundaries for pedestrian encounters, and thereby potentially allowing more efficient design and assessment of active safety systems (Papers IV and V). Integrated assessment will enable the best overall solution for a given development effort, thus improvements in pedestrian protection will be expedited with an integrated, compared to a separated, assessment.

An integrated assessment is necessary as optimising two sub-systems might not result in overall optimisation. For example, it might be beneficial to tune passive safety performance to lower impact speeds when active safety is considered. Providing a certain available deformation space for designing a deformation element, with constant force-deflection characteristics for high impact speeds known to occur without active safety, will result in high reaction forces to take up all impact energy. Knowing that the speed will be lower prior to impact, due to active safety, one might be able to reduce the force level for the same sized element still taking up all impact energy. As reduced reaction forces generally reduce injury probability, the overall protection level would be improved over a design which did not reflect active safety performance on passive safety boundary conditions.

It is hoped that organizations assessing vehicle safety will find it relevant to assess the overall pedestrian safety benefit and adopt the method outlined in Paper VI. If vehicle manufacturers, regulatory and consumer testing organizations were indeed to use an integrated assessment method based on sound evidence, higher overall pedestrian protection could be achieved. Given the length of vehicle development cycles and available roadmaps, such use could be expected from 2020 onward.

This method indicates slightly different priorities for safety design than those which might stem from the 2016 Euro NCAP pedestrian assessment. As shown in Paper II, an A-pillar airbag gives greater benefit in the method developed in this thesis compared to the Euro NCAP rating, while AEB systems have a more limited impact. Currently, several vehicle manufacturers offer pedestrian AEB systems on a variety of car models while only two car models on the European market are equipped with a pedestrian airbag. The current choices of system equipment might be linked to the Euro NCAP rating. Equipment trends with AEB and pedestrian airbags might reverse if the method developed in this thesis were adopted as the basis for a vehicle safety rating.

Paper VI showed that FCW systems can offer benefits of the same order as AEB systems. In Euro NCAP's 2016 pedestrian assessment, FCW systems contribute only marginally to the overall rating, as part of the HMI score, while AEB systems are assessed for their actual speed reduction performance and account for the majority of points available for scoring. Again, were the method developed in this thesis the basis for a vehicle rating that guides vehicle design, priorities might change: FCW systems would gain attention. If FCW systems are cheaper than AEB systems, yet have the potential to offer comparable benefits, vehicle manufacturers might see an incentive to implement FCW systems rather than AEB systems.

The method presented here indicates that the design of fenders for head impact, and in general the very front end of the bonnet, are less of a priority for vehicle design as these areas are less likely to be hit than areas higher on the vehicle front. Euro NCAP gives equal weighting to all impact points, whereas the integrated method is based on actual impact probabilities, revealing that those impact points on the very front end of the bonnet have less influence on overall safety than the Euro NCAP rating would suggest.

The integrated pedestrian assessment method developed here might also guide the future of assessments for other road users, such as cyclists or car occupants. Addressing road user injuries with active and passive safety technology is not specific to pedestrians; the need for integrated assessment to avoid sub-optimization and to achieve the best and most efficient overall protection level is equally important for other road users. Thus, the method developed for pedestrians might be adapted to other road users, replacing input data and relations for pedestrians with data and relations developed for other road users.

4.6 Future research needs

The hypothesis that comfort boundaries are an indicator for acceptance of active safety system activation should be confirmed in a subjective study of driver acceptance of active safety systems making use of predicted driver comfort boundaries for their activation timing. The acceptance could not only be related to timing but also to type of system intervention, with various warnings and automated brake interventions, and to different driver states (attentive, distracted, etc.).

Further influencing factors for comfort boundaries in vehicle-to-pedestrian encounters should be studied. Results from vehicle and pedestrian speeds presented in this thesis should be extended to lower and higher speeds. The influence of other factors (e.g. road width, eye contact, or priority rules, etc.) should be studied. This could provide guidance for deciding on the earliest desired active safety system intervention.

Driver reaction times were studied for distracted drivers in a pedestrian crossing situation with different HMIs. Further studies should confirm that these reaction times are valid for other scenarios, such as pedestrian encounters in longitudinal traffic.

Other limitations of the method presented here should be addressed in future work. For example, further refinement of the assessment of currently untested and linearly related body regions, as well as injury risk curves might increase accuracy. A more detailed model to relate HIC with impact speed for car structures other than bonnets and accounting for bottoming out might be worth developing. Also, injury criteria other than HIC might more accurately reflect injury probability and might replace the use of HIC in this method.

The method integrates hardware test results obtained independently for active and passive safety performances. In the future, it might be possible to rely on mathematical models and simulation to obtain these test results independently or even to use models that allow the simulation of the whole chain of events and truly predict integrated safety benefits. Research is needed to develop such software.

The developed assessment method aims at predicting the overall pedestrian protection offered by vehicles more accurately than current test and rating procedures. The integrated assessment method relies on Euro NCAP test data of the “grid type” for headform impacts introduced in 2011, and on active safety speed reduction data, likely to be publicly available from the introduction of VRU-AEB assessment in Euro NCAP in 2016. Right now, not enough test data is publicly available to calculate alternative assessment scores for a variety of vehicles and compare them with real-life injury outcome. Whether this new method relates assessment scores more closely to real-life safety outcomes than current methods remains to be confirmed.

5 Conclusions

A method to assess the integrated pedestrian safety benefit of AEB and passive technologies has been developed and presented (Paper II). This method, developed from the concept outlined in Paper I, is ready to use. Limitations are presented in Section 4.4. A Matlab program was created to calculate the integrated benefit using separate test data for active and passive safety technologies as input. An example of its use for the assessment of different levels of passive safety, an additional A-Pillar airbag, and AEB was also presented (Paper II). It was shown that an A-pillar airbag gives greater benefit in the method developed in this thesis compared to the Euro NCAP rating, while AEB systems have more limited impact.

Data necessary to model driver reactions to FCW systems was obtained in a Driving Simulator study, showing that reaction rates and response time can be improved when a short brake pulse is added as a haptic warning to an audio-visual warning interface (Paper III).

Based on this data, the method was extended to assess not only AEB but also FCW systems, and illustrated the differences in performance of several FCW systems. It can be seen that both passive and active safety systems have the potential to prevent or mitigate pedestrian casualties with the actual benefit depending on the baseline protection level (without system) and the systems' specific characteristics. The proposed integrated pedestrian safety assessment method can deliver such an integrated, vehicle and system specific assessment. FCW in particular was shown to have the potential to offer benefits comparable to those of AEB, which justifies proposing that FCW is assessed using methods similar to those used for assessing AEB (Paper VI).

The assessed and quantified True Positive performance, that is casualty reduction in collisions, needs to be balanced with driver acceptance. An annoyed driver would turn the system off, ignore it, or not purchase it (again). Driver annoyance is likely to be linked to False Positive performance, which is system activation in situations that would not necessarily evolve into collisions. However, not all False Positive interventions lead to annoyance and it is hypothesized that system activations timed to occur after the individual comfort boundary has passed will not annoy drivers. These comfort boundaries were quantified for pedestrian crossing situations dependent on vehicle and pedestrian speed (Papers IV and V). The comfort boundaries were above 2 s TTC and thereby well above the limits of an unavoidable collision. This implies that systems aiming to reduce impact speed should not intervene only when a collision becomes unavoidable, but earlier, to increase safety benefits without jeopardizing driver acceptance. Besides simply having more time to brake, such intervention timing can also help to familiarize the driver with the system and improve driver reactions.

These comfort boundaries can be used for the important task of setting limits for acceptable activation timing and to guide further False Positive test procedures, complimentary to the developed integrated assessment method.

I recommend implementing the integrated pedestrian safety method in consumer testing to assess the total benefit offered by any combination of active and passive safety systems. The testing for active safety should be expanded to FCW systems, which is straightforward when using driver reactions quantified in this thesis as input to a driving robot triggered by FCW activation. Furthermore, False Positive tests should be implemented. In the test scenarios already in use for the assessment of speed reductions, AEB and FCW system activation before comfort boundary timing should be discouraged. With these proposed activities implemented, assessment could reflect more accurately the total safety benefit offered by different systems and aid proliferation of the most effective and efficient system combinations.

6 References

AAAM. 2008. Abbreviated Injury Scale (AIS) 2005 – Update 2008

Abe G, Richardson J. 2006. Alarm timing, trust and driver expectation for forward collision warning systems. *Applied Ergonomics* 37(5), pp. 577–586

ADAC, 2013. Notbremsassistenten mit Fußgängererkennung 2013 (Emergency brake assist with pedestrian protection). Available at: http://www.adac.de/infotestrat/tests/assistenzsysteme/fussgaengererkennung_2013/default.aspx?ComponentId=192227&SourcePageId=146988

AEB Group. 2011. AEB test procedures. Available at: http://www.trafikverket.se/PageFiles/84153/bilaga_2_aeb_test_procedures_nov11.pdf

Akiyama A, Okamoto M, Rangarajan N. 2001. Development and application of the new pedestrian dummy. *Proceedings of 17th Enhanced Safety of Vehicles (ESV) conference*, Amsterdam, The Netherlands, paper number 463

Anderson RWG, Doecke SD, Mackenzie JRR, Ponte G. 2012. Potential benefits of forward collision avoidance technology. CASR Report 106

Anderson RWG, Searson DJ, Hutchinson TP. 2012. Integrating the assessment of pedestrian safety in vehicles with collision detection and mitigation systems. *Proceedings of IRCOBI conference*, Dublin, Ireland, pp. 751–760

Anderson RWG, Searson DJ. 2014. Use of Age-Period-Cohort models to estimate effects of vehicle age, year of crash and year of vehicle manufacture on driver injury and fatality rates in single vehicle crashes in New South Wales, 2003-2010. *Accident Analysis and Prevention* 75, pp. 202–210

Aoki H, Ozaki O. 2013. Development of a car-following tendency prediction method and its application to a Forward Collision Warning system. *Proceedings of 20th ITS World Congress*, Tokyo, Japan

Bachem HK. 2005. Schutzpotenzial von realisierbaren Lösungen zum fahrzeugseitigen Fußgängerschutz (Potential of pedestrian protection measures offered by vehicles). Dissertation RWTH Aachen University

Banglmaier R, Wang, L, Prasad, P. 2002. Various statistical methods for the analysis of experimental chest compression data. *American Statistical Association, Spring Research Conference* - Section on Physical & Engineering Sciences.

Blincoe L, Seay A, Zaloshnja E, Miller T, Romano E, Luchter S, Spicer R. 2002. The economic impact of motor vehicle crashes, 2000. Report number DOT HS 809 446

Bliss JP, Acton SA. 2003. Alarm mistrust in automobiles: How collision alarm reliability affects driving. *Applied Ergonomics*, 34(6), pp. 499–509

Bovenkerk J., Hardy RN, Neal-Sturgess CE, Hardy BJ, van Schijndel - de Nooij M, Willinger R, Guerra LJ, Martinez L. 2008. Biomechanics of real world injuries and their associated injury criteria. APROSYS, report number AP-SP33-001R

Bromberg S, Oron-Gilad T, Ronen A, Borowsky A, Parmet Y. 2012. The perception of pedestrians from the perspective of elderly experienced and experienced drivers. *Accident Analysis and Prevention* 44, pp. 48-55.

Burgman M. 2005. Risks and decisions for conservation and environmental management. *Cambridge Unversity Press*.

Carhs. 2014. Safety companion. Available at: http://www.carhs.de

Cesari, D. 2008. Future trends of pedestrian safety assessment methods. *Presentation at APROSYS Workshop* in Brussels

DaCoTa. 2012. Pedestrians and cyclists, Deliverable 4.8l of the EC FP7 project DaCoTA

Davis GA. 2001. Relating severity of pedestrian injury to impact speed in vehicle pedestrian crashes. *Transport Research Record Record No. 1773*, 108–113

EC Regulation of the European Parliament and of the Council No 78/2009. 2009a. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:035:0001:0031:EN:PDF

EC Commission Regulation No 631/2009. 2009b. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:195:0001:0060:EN:PDF

Edwards M, Nathanson A, Wisch M. 2014a. Estimate of potential benefit for Europe of fitting Autonomous Emergency Braking (AEB) systems for pedestrian protection to cars. *Traffic Injury Prevention* 15 sup1, pp. 173–182

Edwards M, Nathanson A, Carroll J, Wisch M, Zander O, Lubbe N. 2014b. Proposal for test and assessment protocol for pedestrian pre-crash systems. Deliverable D1.4 of the AsPeCSS project. Available at: http://www.aspecss-project.eu/downloads/

EEVC. 2002. Improved test methods to evaluate pedestrian protection afforded by passenger cars (December 1998 with September 2002 updates). EEVC Working Group 17 Report. Available at: http://eevc.org/publicdocs/publicdocs.htm

Eggers A, Schwedhelm H, Zander O, Izquierdo RC, Polanco JAG, Seibert D, Jacob C. 2013. Virtual testing based type approval procedures for the assessment of pedestrian protection developed within the EU-Project IMVITER. *Proceedings of 23rd Enhanced Safety of Vehicles (ESV) conference*, Soul, Republic of Korea, paper number 13-0344

Erbsmehl C. 2009. Simulation of real crashes as a method for estimating the potential benefits of advanced safety technologies. *Proceedings of 21st Enhanced Safety of Vehicles (ESV) conference*, Stuttgart, Germany, paper number 09-0162

Euro NCAP. 2015a. Assessment protocol – Pedestrian protection. Version 8.0. Available at: http://www.euroncap.com

Euro NCAP. 2015b. Pedestrian testing protocol. Version 8.0. Available at: http://www.euroncap.com

Euro NCAP. 2015c. Assessment protocol – Pedestrian protection. Version 8.1. Available at: http://www.euroncap.com

Euro NCAP. 2015d. Test protocol – AEB systems. Version 1.1. Available at: http://www.euroncap.com

Euro NCAP. 2015e. 2020 Roadmap. Revision 1. Available at: http://www.euroncap.com

Euro NCAP. 2015f. Test protocol – AEB VRU systems, Version 1.0.1. Available at: http://www.euroncap.com

Fredriksson R, Rosén E, Kullgren A. 2011. Priorities of pedestrian protection - A real-life study of severe injuries and car sources. *Accident Analysis and Prevention*, 42(6), pp. 1672–1681

Fredriksson R. 2011. Priorities and potential of pedestrian protection. Accident data, experimental tests and numerical simulations of car-to-pedestrian impacts. Dissertation Karolinska Institutet

Fredriksson R, Rosén E. 2012. Integrated pedestrian countermeasures – Potential of head injury reduction combining passive and active countermeasures, *Safety Science* 50, pp. 400–407

Gustafsson H, Nygren Å, Tingvall C. 1985. Rating system for serious consequences (RSC) due to traffic accidents – Risk of death or permanent disability. *Proceedings of the 10th Technical Conference on Experimental Safety Vehicles*. Oxford, United Kingdom, pp. 556–560

Hamacher M, Eckstein L, Kühn M, Hummel T. 2011. Assessment of active and passive technical measures for pedestrian protection at the vehicle front. *Proceedings of 22nd Enhanced Safety of Vehicles (ESV) conference*, Washington DC, USA, paper number 11-0057

Hamacher M, Eckstein L, Kühn M, Hummel T. 2013. Integrated pedestrian safety assessment procedure. *Proceedings of 23rd Enhanced Safety of Vehicles (ESV) conference*, Soul, Republic of Korea, paper number 13-0268

Hamacher M. 2014. Integriertes Fußgängerschutz-Bewertungsverfahren für Kraftfahrzeuge (Integrated Pedestrian Safety Assessment of Vehicles). Dissertation RWTH Aachen University

Hamada M, Hasegawa J, Nishimura R. 2005. Application of EEVC upper leg impactor test method to SUVs-Finite Element analysis of pedestrian pelvic injuries. *JSAE transactions*, Vol. 36, pp. 201–206

Han Y, Yang J, Mizuno K, Matsui Y. 2012. A study on chest injury mechanism and the effectiveness of a headform impact test for pedestrian chest protection from vehicle collisions. *Safety Science* 50(5), pp. 1304–1312

Helmer T. 2014. Development of a methodology for the evaluation of active safety using the example of preventive pedestrian protection. Dissertation Technical University Berlin

Homma R, Kikuchi K, Wakasugi T, Tasaka T, Yoshida S. 2014. Evaluation of forward-vehicle collision-avoidance systems – How drivers respond to warnings when a hazardous situation is not expected. Presented at *12th International Symposium on Advanced Vehicle Control*, Tokyo, Japan

Hertz E. 1993. A Note on the Head Injury Criterion (HIC) as a predictor of the risk of skull fracture. In: 37th Annual Proceedings, *Association for the Advanceent of Automotive Medicine (AAAM)*, pp. 303-311

Hutchinson TP, Anderson RWG, Searson DJ. 2012. Pedestrian headform testing: Inferring performance at impact speeds and for headform masses not tested, and estimating average performance in a range of real-world conditions. *Traffic Injury Prevention 13(4)*, pp. 402–411

ITARDA. 2011. Nighttime fatal accidents involving senior pedestrians. *ITARDA information No. 87.* Available at: http://www.itarda.or.jp/itardainfomation/english/info87_e.pdf

ITARDA. 2012. Accidents resulting in pedestrian fatalities occur most frequently with vehicles proceeding straight ahead. *ITARDA information No. 94.* Available at: http://www.itarda.or.jp/itardainfomation/english/info94_e.pdf

JNCAP. 2013. Car Safety Performance Guidebook. Available at: http://www.nasva.go.jp/

JNCAP. 2014a. 平成 23 年度歩行者頭部保護性能試験方法（本文）(Pedestrian head protection performance test method in 2011) Available at: http://www.nasva.go.jp/

JNCAP. 2014b. 平成 23 年度歩行者脚部保護性能試験方法（本文）(Pedestrian leg protection performance test method in 2011) Available at: http://www.nasva.go.jp/

Kahneman, D. 2011. Thinking, fast and slow. *Penguin books*.

Källhammer JE. 2011. Using false alarms when developing automotive active safety systems. Dissertation Linköping University

Källhammer JE, Smith K, Hollnagel E. 2014. An empirical method for quantifying drivers' level of acceptance of alerts issued by automotive active safety systems. In: Regan MA, Horberry T, Stevens A (Eds.) Driver Acceptance of New Technology. Theory, measurement and optimisation. *Ashgate.*

Katsuhara T, Miyazaki H, Kitagawa Y, Yasuki T. 2014. Impact kinematics of cyclist and head injury mechanism in car-to-bicycle collision. *Proceedings of IRCOBI conference*, Berlin, Germany, pp. 670–684

Kerrigan J, Crandall J, Deng B. 2007. Pedestrian kinematic response to mid-sized vehicle impact. *International Journal of Vehicle Safety* Vol 2 (3), pp. 221-240

Kerrigan J, Arregui C, Crandall J. 2009. Pedestrian head impact dynamics: Comparison of dummy and PMHS in small sedan and large SUV impacts. *Proceedings of 21st Enhanced Safety of Vehicles (ESV) conference*, Stuttgart, Germany, paper number 09-0127

Kiuchi T, Lubbe N, Otte D, Chen Q. 2014. Comparative study of VRU head impact locations. *6th International Conference on Expert Symposium on Accident Research (ESAR)*, Hannover, Germany

Kompass K. 2012. Accident Research 2.0: New methods for representative evaluation of integral safety in traffic. *5th International Conference on Expert Symposium on Accident Research (ESAR)*, Hannover, Germany

Kühn M, Fröming F, Schindler V. 2005. Assessment of vehicle related pedestrian safety. *Proceedings of 19th Enhanced Safety of Vehicles (ESV) conference*, Washington DC, USA, paper number 05-0044

Kühn M, Fröming F, Schindler V. 2007. Fußgängerschutz. Unfallgeschehen, Fahrzeuggestaltung, Testverfahren (Pedestrian protection. Accidents, vehicle design, test methods), *Springer*

Lawrence GJL, Hardy BJ, Carroll JA, Donaldson WMS, Visvikis C, Peel DA. 2006. A study on the feasibility of measures relating to the protection of pedestrians and other vulnerable road users – Final 2006. Updated by Hardy BJ, Lawrence GJL, Knight IM and Carroll JA. Project Report UPR/VE/045/06 under Contract No. ENTR/05/17.01 to the European Commission.

Lawrence GJL. 2005. The next steps for pedestrian protection test methods. *Proceedings of 19th Enhanced Safety of Vehicles (ESV) conference*, Washington DC, USA, paper number 05-0379

Lees MN, Lee JD. 2008. Enhancing Safety by augmenting information acquisition in the driving environment. In: Castro, C (Ed) Human factors of visual and cognitive performance in driving. *Taylor & Francis.*

Lemmen P, Stoll J, Bergelt U, Seiniger P, Wisch M, Bartels O, Schubert E, Kunert M, Knight I, Brookes D, Ranovona M, Okawa T, Domsch C, Schaller T. 2013. Evaluation of pedestrian targets used in AEB testing: A report from Harmonistion Platform 2 dealing with test equipment.

Proceedings of 23rd Enhanced Safety of Vehicles (ESV) conference, Soul, Republic of Korea, paper number 13-0124
Liers H, Hannawald L. 2009. Benefit estimation of the Euro NCAP pedestrian rating concerning real-world pedestrian safety, Report under contract of ACEA
Liers H. 2010. Extension of the Euro NCAP effectiveness study with focus on MAIS3+ injured pedestrians, Report under contract of ACEA
Lindman M, Ödblom A, Bergvall E, Eidehall A, Svanberg B, Lukaszewicz T. 2010. Benefit estimation model for pedestrian auto brake functionality. *4th International Conference on Expert Symposium on Accident Research (ESAR)*, Hannover, Germany
Ljung Aust M, Engström J. 2011. A conceptual framework for requirement specification and evaluation of active safety functions. *Theoretical Issues in Ergonomics Science* 12(1), pp. 44–65
Ljung Aust M, Dombrovskis S. 2013. Understanding and improving driver compliance with safety system feedback. *Proceedings of the 23rd International Technical Conference on the Enhanced Safety of Vehicles*, Seoul, Republic of Korea, paper number 13-0455
Malm S, Krafft M, Kullgren A, Ydenius A, Tingvall C. 2008. Risk of permanent medical impairment (RPMI) in road traffic accidents. *Ann Adv Automot Med*, Vol. 52 pp. 293–300
Montgomery J, Kusano K D, Gabler H C. 2014. Age and gender differences in Time To Collision at braking from the 100-car naturalistic driving study. Traffic Injury Prevention, 15 Suppl. 1, 15–20
Mottola E, Rodarius C, Schaub S. 2013. Pedestrian kinematics and specifications of new impact conditions for head- and leg-form impactors. Deliverable D3.1 of the AsPeCSS project. Available at: http://www.aspecss-project.eu/downloads/
Martin JL, Audrey L, Laumon B. 2011. Pedestrian injury patterns according to car and causality characteristics in France. *Ann Adv Automot Med.*, Vol 55 pp. 137–146
Martinez WL, Martinez AR. 2008. Computational statistics handbook with Matlab. 2nd Edition, *Chapman & Hall*
Matsui. Y. 2003. New injury reference values determined for TRL legform impactor from accident reconstruction test. *International Journal of Crashworthiness 8* (2) 179–188.
Matsui Y. 2004. Proposal of injury risk curves for evaluating pedestrian head injury risk using headform impactor based on accident reconstruction. Japanese (English abstract, tables and figures). JSAE paper 20044764, *JSAE Transactions*, 35 (4) 221–228
Matsui Y, Ha Y, Mizuno K. 2011. Performance of collision damage mitigation braking systems and their effects on human injury in the event of car-to-pedestrian accidents. *Stapp Car Crash Journal*, Vol. 55, pp. 461–478
Mueller BC, Nolan JM, Zuby DS, Rizzo AG. 2012. Pedestrian injury patterns in the United States and relevance to gtr. *Proceedings of IRCOBI conference*, Dublin, Ireland, pp. 690–702
Nakahira Y, Furukawa K, Niimi H, Ishihara T, Miki K, Matsuoka F. 2000. A combined evaluation method and a modified Maximum Likelihood method for injury risk curves. Proceedings of *IRCOBI Conference*, Montpellier, France
NHTSA. 1995. Final economic assessment, FMVSS No. 201, upper interior head protection. Report number NHTSA-1996-1762 item ID-0003. Available at: http://www.regulations.gov/#!documentDetail;D=NHTSA-1996-1762-0003
NHTSA. 2014. Traffic safety facts: Pedestrian. DOT HS 811 888
Niewöhner W, Roth F, Gwehenberger J, Gruber C, Kuehn M, Sferco R, Pastor CH, Nagel U, Stanzel M. 2011. Proposal for a test procedure of assistance systems regarding preventive pedestrian protection. *Proceedings of 22nd Enhanced Safety of Vehicles (ESV) conference*, Washington DC, USA, paper number 11-0393
OECD. 2008. Towards zero: Achieving ambitious road safety targets through a safe system approach, Organization for Economic Co-operation and Development, Paris
Otubushin A, Gruber C, Domsch C. 2011. BMW Integrale Sicherheit: Effektive Schutzmöglichkeiten Schwächerer Verkehrsteilnehmer. (Integrated safety: Effective possibilities to protect Vulnerable Road Users) *6th Praxiskonferenz Fußgängerschutz*, Bergisch-Gladbach
Paas R, Östh J, Davidsson J. 2015. Which pragmatic Finite Element human body model scaling technique can most accurately predict head-impact conditions in pedestrian-car crashes? *Proceedings of IRCOBI conference*, Lyon, France

Pace JF, Tormo MT, Sanmartin J *et al*. 2012. Basic fact sheet "Pedestrians", Deliverable D3.9 of the EC FP7 project DaCoTA

Peng Y, Deck C, Yang J, Cesari D, Willinger R. 2011. Adult and child pedestrian head impact condition as a function of vehicle front end geometry. *Proceedings of IRCOBI conference,* Krakow, Poland, pp. 277–281

Prasad P, Mertz H. 1985. The position of the United States delegation to the ISO Working Group 6 on the use of HIC in the automotive environment. SAE Government/Industry meeting and exposition, SAE paper number 851246

Rizzi M, Strandroth J, Sternlund S, Tingvall C, Fildes B. 2012. Motorcycle crashes into road barriers: The role of stability and different types of barriers for injury outcome. *Proceedings of IRCOBI conference*, Dublin, Ireland, pp. 328–341

Rodarius C, Elrofai H, Meijer R, Nuß F. 2014. Data analysis for construction of injury risk curves. Deliverable D3.3 of the AsPeCSS project. Available at: http://www.aspecss-project.eu/downloads/

Rodmell C, Lawrence GJL. 1998. Comparison between dose-response and cumulative methods of injury risk analysis and implications on the JARI injury risk analysis. TRL committee paper for EEVC WG17, Doc 111

Rosén E, Sander U. 2009. Pedestrian fatality risk as a function of car impact speed. *Accident Analysis and Prevention* 41, pp. 536–542

Rosén E, Källhammer JE, Eriksson D, Netwich M, Fredriksson R, Smith K. 2010. Pedestrian injury mitigation by autonomous braking. *Accident Analysis and Prevention* 42, pp.1949–1957

Rosén E. 2013. Autonomous Emergency Braking for Vulnerable Road Users. *Proceedings of IRCOBI conference*, Gothenburg, Sweden, pp. 618–627

Roth F, Stoll J. 2011. Integrated pedestrian protection. *6th Praxiskonferenz Fußgängerschutz*, Bergisch-Gladbach

Saez LM, Casanova LJG, Fazio EA, Alvarez AG. 2012. Behaviour of high bumper vehicles in pedestrian scenarios with full finite element human models. *Int. J. of Crashworthiness*. 17(1) pp. 1–10

Schmitt KU, Niederer PF, Muser MH, Walz F. 2004. Trauma biomechanics: Introduction to accidental injury. 1st Edition, *Springer*

Schram R, Williams A, van Ratingen M, Ryberg S, Sferco R. 2015. Euro NCAP's first step to assess Autonomous Emergency braking (AEB) for Vulnerable Road Users. *Proceedings of 24th Enhanced Safety of Vehicles (ESV) conference*, Gothenburg, Sweden, paper number 15-0277

Schramm S. 2011. Methode zur Berechnung der Feldeffektivität integraler Fußgängerschutzsysteme (Method to calculate field effectiveness of integrated pedestrian protection systems). Dissertation Technical University Munich.

Searson DJ, Anderson RWG. 2010. Implications of easing head impact criteria in pedestrian crash standards. CASR Report 083

Searson DJ, Anderson RWG, Hutchinson TP. 2012a. The effect of impact speed on the HIC obtained in pedestrian headform tests. *International Journal of Crashworthiness* 17(5), pp. 562–570

Searson DJ, Hutchinson TP, Anderson RWG. 2012b. From crash test speed to performance in real world conditions. A conceptual model and its application to underhood clearance in pedestrian head tests. *Stapp Car Crash Journal*, Vol. 56, pp. 485–496

Searson DJ, Anderson RWG, Hutchinson TP. 2014. Integrated assessment of pedestrian head impact protection in testing secondary safety and autonomous emergency braking. *Accident Analysis and Prevention* 63, pp. 1–8

Seiniger P, Bartels O, Pastor C, Wisch M. 2013. An open simulation approach to identify chances and limitations for Vulnerable Road User (VRU) active safety. *Traffic Injury Prevention* 14, pp. 2–12

Seiniger P, Schubert E, Kunert M. 2014. Test procedure including test target and misuse tests, based on test results. Deliverable D2.5 of the AsPeCSS project. Available at: http://www.aspecss-project.eu/downloads/

Seo BP, Park YJ, Han SJ, Battaglia S. 2014. Crashworthiness improvement through integrated analysis of active and passive safety systems. *FISITA World Automotive Congress*, Maastricht, The Netherlands, paper number 2014-AST-016

Shigeta K, Kitagawa Y, Yasuki T. 2009. Development of next generation human FE model capable of organ injury prediction. *Proceedings of 21st Enhanced Safety of Vehicles (ESV) conference*, Stuttgart, Germany, paper number 09-0111

Snedeker JG, Muser MH, Walz FH. 2003. Assessment of pelvis and upper leg injury risk in car-pedestrian collisions: Comparison of accident statistics, impactor tests and a human body Finite Element model. *Stapp Car Crash Journal*, Vol. 47, pp. 437–457

Stigsson H, Gustafsson M, Sunnevång C, Krafft M, Kullgren A. 2015. Differences in long-term medical consequences depending on impact direction involving passenger cars, *Traffic Injury Prevention*, 16:sup1, pp. 133-139

Strandroth J, Rizzi M, Sternlund S, Lie A, Tingvall C. 2011. The correlation between pedestrian injury severity in real-life crashes and Euro NCAP pedestrian test results. *Traffic Injury Prevention*, 12:6, pp. 604–613

Strandroth J, Sternlund S, Tingvall C, Johansson R, Rizzi M, Kullgren A. 2012. A new method to evaluate future impact of vehicle safety technology in Sweden. *Stapp Car Crash Journal* Vol. 56, pp. 497–509

Takhounts E. 2015. Modern perspective on historical brain injury research. Keynote Lecture at *IRCOBI conference*, Lyon, France

Takahashi Y, Matsuoka F, Okuyama H, Imaizumi I. 2012. Development of injury probability functions for the Flexible Pedestrian Legform Impactor., *SAE Int. J. Passeng. Cars - Mech. Syst.* Vol. 5 (1)

Tanaka S, Teraoka EYM. 2014. Benefit estimation of active safety systems for crossing-pedestrian scenarios. *FISITA World Automotive Congress*, Maastricht, The Netherlands, paper number 2014-AST-006

Tass. 2015. PreScan: Simulation of ADAS & active safety. Available at: https://www.tassinternational.com/prescan

Tefft BC. 2011. Impact speed and a pedestrian's risk of severe injury or death. *AAA Foundation for Traffic Safety*, Washington DC, USA. Available at: https://www.aaafoundation.org/sites/default/files/2011PedestrianRiskVsSpeed.pdf

Teraoka EYM, Tanaka S, Mochida T. 2013. Benefit estimation of active safety systems for crossing-pedestrian scenarios. *Fast-zero conference*, Nagoya, Japan, paper number 009

Tingvall C, Haworth N. 1999. Vision Zero - An ethical approach to safety and mobility. *6th ITE International Conference Road Safety & Traffic Enforcement: Beyond 2000*, Melbourne, Australia

Tingvall C, Ifver J, Krafft M, Kullgren A, Lie A, Rizzi M, Sternlund S, Stigson H, Strandroth J. 2013. The consequences of adopting a MAIS 3 injury target for road safety in the EU: A comparison with targets based on fatalities and long-term consequences. *Proceedings of IRCOBI conference*, Gothenburg, Sweden

Toyota. 2013. Toyota develops new pedestrian safety technology. Press release, October 11, 2013

Trafikverket. 2012. Säker Trafik - Nollvisionen på väg. (Safe traffic – vision zero on the move) Document number 1005032012. Available at: http://publikationswebbutik.vv.se/upload/6562/100503_saker_trafik_nollvisionen_pa_vag.pdf

van der Made R. 2015. Virtual testing using probabilistic radar sensor simulations. Presented at *Autonomous Vehicle Test & Development Symposium*, Stuttgart, Germany

van Ratingen M, Williams A, Castaing P, Lie A, Frost B, Sander V, Sferco R, Segers E, Weimar C. Beyond NCAP: Promoting new advancements in safety. 2011. *Proceedings of 22nd Enhanced Safety of Vehicles (ESV) conference*, Washington DC, USA, paper number 11-0075

vFSS. 2012a. Vorausschauender Fußgängerschutz: Testverfahren zur Vergleichbarkeit der Effizienz präventiver Fußgängerschutzsysteme V0.19 (Preventive pedestrian protection: Test methods for comparative assessment of preventive pedestrian protection). Available at: www.vfss.net

vFSS. 2012b. Effectiveness evaluation of advanced forward looking safety systems. Status presentation 14 March 2012. Available at: www.vfss.net

vFSS. 2012c. Active pedestrian safety – Development of a harmonised test procedure. Active Test Workshop, Boras, Sweden. Available at: www.activetest.eu

Watanabe R, Miyazaki H, Kitagawa Y, Yasuki T. 2011. Research of collision speed dependency of pedestrian head and chest injuries using human FE model (THUMS version 4). *Proceedings of*

22nd Enhanced Safety of Vehicles (ESV) conference, Washington DC, USA, paper number 11-0043

Watanabe R, Katsuhara T, Miyazaki H, Kitagawa Y, Yasuki T. 2012. Research of the relationship of pedestrian injury to collision speed, car-type, impact location and pedestrian sizes using human FE model (THUMS version 4). *Stapp Car Crash Journal* Vol 56, pp. 269–322

Weaver AA, Barnard RT, Kilgo PD, Martin RS, Stitzel JD. 2013. Mortality-based quantification of injury severity for frequently occurring motor vehicle crash injuries. *Ann Adv Automot Med*, Vol. 57, pp. 235–246

WHO. 2011. Decade of action for road safety 2011-2020. Saving millions of lives. Available at: http://www.who.int/violence_injury_prevention/publications/road_traffic/saving_millions_lives_en.pdf?ua=1

Wisch M, Seiniger P, Pastor C, Edwards M, Visvikis C, Reeves C. 2013. Scenarios and weighting factors for pre-crash assessment of integrated pedestrian safety systems. Deliverable D1.1 of the AsPeCSS project. Available at: http://www.aspecss-project.eu

Wittink R. 2001. Promotion of mobility and safety of vulnerable road users, Report of the PROMISING project. Available at: http://www.swov.nl/rapport/d-2001-03.pdf

Yanagisawa M, Swanson E, Najm WG. 2014. Target crashes and safety benefits estimation methodology for pedestrian crash avoidance/mitigation systems. Report number DOT HS 811 998

Yasuki T. 2006. Using THUMS for pedestrian safety simulations. *Auto Technology* Vol 6 (4), pp. 44-47

Zaloshnja E, Miller T, Romano E, Spicer R. 2004. Crash costs by body part injured, fracture involvement, and threat-to-life severity. United States, 2000. *Accident Analysis and Prevention,* 36, pp. 415–427

Zander O, Gehring DU, van Ratingen M. 2015. Beyond safety legislation: Contribution of consumer information programmes to enhanced injury mitigation of pedestrians during accidents with motor vehicles. *Proceedings of 24th Enhanced Safety of Vehicles (ESV) conference*, Gothenburg, Sweden, paper number 15-0258

Appendix 1: Sensitivity Analyses

1.1 Sensitivity to assumptions for HIC mapping and non-tested areas

The integrated assessment method is used to calculate casualty cost for an example vehicle. The assessment method in this thesis maps Euro NCAP test points to a HIC map used for the calculation of casualty cost. The details of the mapping procedures applied in Papers II and VI are explained below. Consequences of the mapping procedures are highlighted. These consequences are contrasted with those from an implementation of an alternative mapping procedure from the VERPS method into the integrated assessment method. Casualty costs are calculated with this alternative method ("Paper VI with VERPS mapping") and compared to the method proposed.

The Euro NCAP headform test area with impact points is depicted in Figure 9 (from Euro NCAP, 2015b). In the longitudinal direction, the impact area is bound by WAD 1000 and WAD 2100 lines. These WAD lines follow the vehicle front shape while impact point are drawn laterally originating from centreline without consideration of the front shape. In consequence, apart from centreline, impact points are not necessarily located on a WAD line.

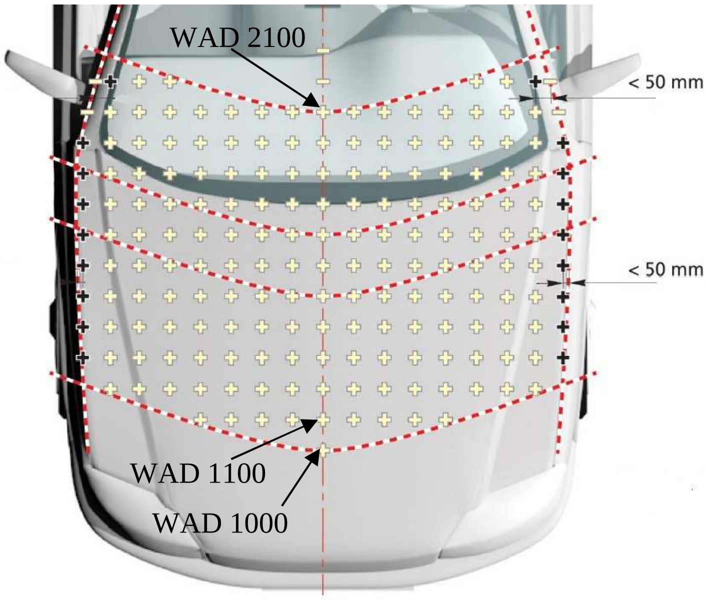


Figure 9 . Euro NCAP head impact test grid marking

The integrated assessment method assigns impact points to WAD locations based on centreline impact points. That means that all impact points laterally from the centreline point are assigned the same WAD. In Figure 9 therefore, only one point, the centre point, is assigned to WAD1000; the centre point and four points to left and right are assigned to WAD 1100; and so on. At the upper test area boundary, WAD 2100 is assigned to a total of 15 points in a straight line. Notably, three points on the left and right of the vehicle are located above this straight line and are assigned WAD 2200, even though no such centre point exists. In consequence, the upper WAD limit for the integrated assessment method will vary depending on vehicle shape and a top row of test points will consist of only a few points exceeding WAD 2100.

The implications of this procedure of assigning WAD to impact points together with the procedure of using only impact points which were assessed were calculated using the assessment method outlined in Paper VI. Inputs to the method are HIC values for a vehicle's front end structure representative of a "good" Euro NCAP performance without any active safety system intervention. In Figure 10, HIC values for impact points are depicted in a top view (vehicle front to the left, increasing WAD to the right). "Green" areas with low HIC values can be found in the middle of the bonnet and in the windscreen area; "red" areas are the A-pillars with assumed HIC 6000 and the vicinity of the A-pillar with HIC 2000. Notably, there is only one test point on the vehicle front assigned WAD 1000 and only four test points assigned WAD 2200 on and near the A-pillar.

								2000	6000	6000	6000	6000
		825	825	825	1175	825	1175	1175	1175	2000	2000	2000
	825	825	825	825	825	825	825	1175	1175	825	475	
	825	825	825	475	475	825	825	825	1175	825	475	
	825	475	475	475	475	825	825	825	1175	825	475	
	475	475	475	475	475	825	475	825	1175	825	475	
	475	475	475	475	475	475	475	825	825	475	475	
825	475	475	475	475	475	475	475	475	825	475	475	
	475	475	475	475	475	825	825	825	825	475	475	
	475	475	475	475	475	825	825	825	1175	825	475	
	825	475	475	475	475	825	1175	825	1175	825	475	
	825	825	825	475	475	825	825	825	1175	825	475	
	825	825	825	825	825	825	1175	1175	1175	825	475	
		825	825	825	1175	825	1175	1175	1175	2000	2000	2000
								2000	6000	6000	6000	6000

Figure 10. Head Impact Criterion Map (input to assessment)

The relative distribution of resulting cost for head injuries for pedestrians calculated with the integrated assessment method is depicted in Figure 11. This representation of assessment results can guide vehicle designers to areas that would benefit most (in terms of casualty cost) from design changes. Notably, the bonnet area contributes little to overall head injury cost while the A-pillars and in particular the highest point (at assigned WAD 2200) contribute with over 16% each. For the complete pedestrian population, A-pillars cause the majority (61%) of head injury costs.

								0.66%	4.28%	5.17%	5.05%	16.22%
		0.05%	0.08%	0.11%	0.21%	0.13%	0.24%	0.27%	0.43%	1.52%	1.69%	5.93%
	0.03%	0.05%	0.08%	0.11%	0.13%	0.13%	0.14%	0.27%	0.43%	0.34%	0.15%	
	0.03%	0.05%	0.08%	0.04%	0.05%	0.13%	0.14%	0.15%	0.43%	0.34%	0.15%	
	0.03%	0.02%	0.03%	0.04%	0.05%	0.13%	0.14%	0.15%	0.43%	0.34%	0.15%	
	0.01%	0.02%	0.03%	0.04%	0.05%	0.13%	0.06%	0.15%	0.43%	0.34%	0.15%	
	0.01%	0.02%	0.03%	0.04%	0.05%	0.06%	0.06%	0.15%	0.23%	0.11%	0.15%	
0.10%	0.01%	0.02%	0.03%	0.04%	0.05%	0.06%	0.06%	0.06%	0.23%	0.11%	0.15%	
	0.01%	0.02%	0.03%	0.04%	0.05%	0.13%	0.14%	0.15%	0.23%	0.11%	0.15%	
	0.01%	0.02%	0.03%	0.04%	0.05%	0.13%	0.14%	0.15%	0.43%	0.34%	0.15%	
	0.03%	0.02%	0.03%	0.04%	0.05%	0.13%	0.24%	0.15%	0.43%	0.34%	0.15%	
	0.03%	0.05%	0.08%	0.04%	0.05%	0.13%	0.14%	0.15%	0.43%	0.34%	0.15%	
	0.03%	0.05%	0.08%	0.11%	0.13%	0.13%	0.24%	0.27%	0.43%	0.34%	0.15%	
		0.05%	0.08%	0.11%	0.21%	0.13%	0.24%	0.27%	0.43%	1.52%	1.69%	5.93%
								0.66%	4.28%	5.17%	5.05%	16.22%

Figure 11. Relative head injury cost of the proposed assessment method (output)

If impacts on the windscreen for unassessed impact points at assigned WAD2200 (as is done for VERPS) are used as a hypothetical alternative input to the assessment method in this thesis, the total head injury cost and distribution changes substantially. As predicted impacts at WAD 2200 are distributed over 15 points laterally instead of four, each of the original four points has a lower probability of impact (changing from ¼ of all predicted impacts at WAD2200 to 1/15). The highest A-pillar impact points are predicted to be hit less often. Compared to the calculation of head injury cost with the proposed assessment method (Paper VI), both the absolute and relative contribution to head injury cost decreases (Figure 12). The overall predicted head injury costs decrease to 69% of the original total head injury cost, A-pillars contribute with 54% (down from 61%) and the contribution of the two highest A-pillar impact points together decrease from 32% to 12%. Notably, the highest contribution to injury cost comes from A-pillar points at assigned WAD 2000 and 2100, rather than those assigned WAD 2200.

There are some design implications. Practically, to improve scores in the proposed integrated assessment method, it seems particularly effective to change the design of the A-pillars to include a softer material towards the impact side or to alter the vehicle geometry so as to include more impact points in the top WAD rank. Changes to the bonnet and windscreen area appear to be of little relevance. Using VERPS mapping, A-pillar changes appear likewise to be most effective, while changes to bonnet and windscreen area get higher relevance. Changes to the vehicle geometry appear to be not relevant, as hypothetical test results are added to the highest WAD rank, ensuring that this rank is not sparsely populated.

								0.95%	6.16%	7.44%	7.26%	6.23%
		0.07%	0.12%	0.16%	0.30%	0.19%	0.34%	0.39%	0.62%	2.19%	2.43%	2.27%
	0.04%	0.07%	0.12%	0.16%	0.18%	0.19%	0.21%	0.39%	0.62%	0.48%	0.22%	0.26%
	0.04%	0.07%	0.12%	0.06%	0.08%	0.19%	0.21%	0.22%	0.62%	0.48%	0.22%	0.26%
	0.04%	0.02%	0.04%	0.06%	0.08%	0.19%	0.21%	0.22%	0.62%	0.48%	0.22%	0.26%
	0.01%	0.02%	0.04%	0.06%	0.08%	0.19%	0.09%	0.22%	0.62%	0.48%	0.22%	0.26%
	0.01%	0.02%	0.04%	0.06%	0.08%	0.08%	0.09%	0.22%	0.33%	0.16%	0.22%	0.26%
0.15%	0.01%	0.02%	0.04%	0.06%	0.08%	0.08%	0.09%	0.09%	0.33%	0.16%	0.22%	0.26%
	0.01%	0.02%	0.04%	0.06%	0.08%	0.19%	0.21%	0.22%	0.33%	0.16%	0.22%	0.26%
	0.01%	0.02%	0.04%	0.06%	0.08%	0.19%	0.21%	0.22%	0.62%	0.48%	0.22%	0.26%
	0.04%	0.02%	0.04%	0.06%	0.08%	0.19%	0.34%	0.22%	0.62%	0.48%	0.22%	0.26%
	0.04%	0.07%	0.12%	0.06%	0.08%	0.19%	0.21%	0.22%	0.62%	0.48%	0.22%	0.26%
	0.04%	0.07%	0.12%	0.16%	0.18%	0.19%	0.34%	0.39%	0.62%	0.48%	0.22%	0.26%
		0.07%	0.12%	0.16%	0.30%	0.19%	0.34%	0.39%	0.62%	2.19%	2.43%	2.27%
								0.95%	6.16%	7.44%	7.26%	6.23%

Figure 12. Relative head injury cost map assuming windscreen impact (with HIC 475) at unassessed impact points on WAD 2200 (hypothetical, alternative assessment output)

1.2 Sensitivity to variations in the gender distribution

The assessment method in this thesis calculates casualty cost for a pedestrian population consisting of one third adult males, one third adult females, and one third children. The representative height of these populations are taken from United Kingdom data and used to calculate impact probabilities of the head in terms of WAD dependent on vehicle impact speed as depicted in Figure 13. The relation depicted is based on the THUMS and MADYMO simulation (Mottola *et al*., 2013; paper II). For this population, casualty costs are calculated with the method presented in Paper VI and can be attributed to certain areas of the vehicle as given in Figure 11, which depicts the assessment output for a vehicle representative of “good” Euro NCAP performance.

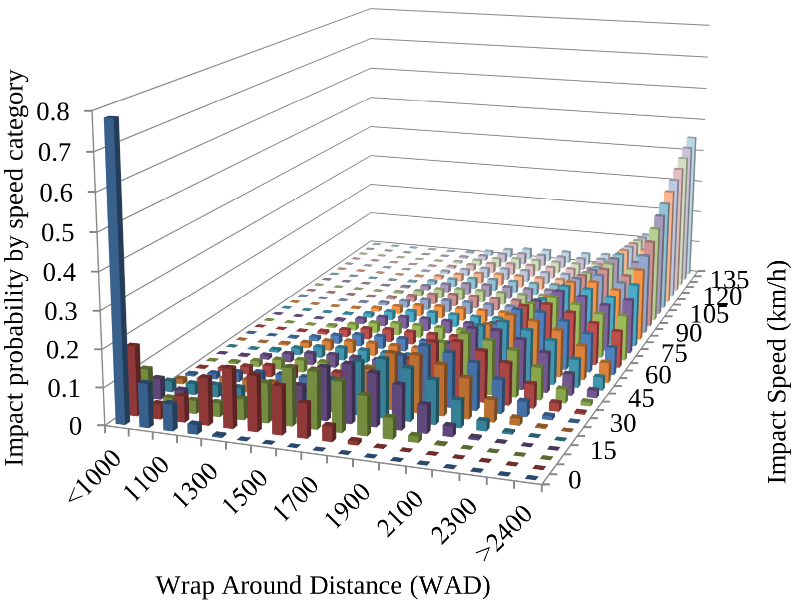


Figure 13 . Probability of impacts at specific WAD dependent on speed (assessment input)

If a hypothetical alternative assessment outcome is calculated using the method of Paper VI but only for male adults with an average height of 176 cm (standard deviation 70 cm), the tallest group, overall casualty costs are about 17% higher compared to the entire population. The importance of the A-pillar is more pronounced compared to the complete population, with 78% of all head injury cost resulting from A-pillar areas. The bonnet area causes practically no head injury cost, as can be seen from the relative distribution of resulting cost for head injuries shown in Figure 14.

Substituting the pedestrian height distribution to that of adult females with an average height of 162 cm (standard deviation 64 cm), the resulting overall casualty costs are similar to those of adult males and about 18% higher than the entire pedestrian population. A-pillars again represent the majority (61%) of head injury costs, but the highest points are less dominant (9% each) (Figure 15). Finally, changing the input height distribution to that for children, overall head injury costs drop to about 65% of that of the complete population, indicating that the example car offers better protection for children than for adults. A-pillars account for 33% of child head injury cost and the bonnet area has a higher relative importance compared to adults (Figure 16).

Relative head injury cost for given car structures and impact areas therefore vary with gender through different average heights. The effect is more pronounced when looking at larger height differences, such as the difference between children and adults. However, those vehicle front end structures which need to be prioritized to reduce casualty costs remain fairly stable for each gender in isolation.

								0.03%	0.94%	2.86%	5.85%	29.32%
		0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.04%	0.47%	1.25%	8.22%
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.04%	0.07%	0.06%	
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.04%	0.07%	0.06%	
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.04%	0.07%	0.06%	
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.04%	0.07%	0.06%	
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.02%	0.03%	0.06%	
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.02%	0.03%	0.06%	
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.02%	0.03%	0.06%	
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.04%	0.07%	0.06%	
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.04%	0.07%	0.06%	
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.04%	0.07%	0.06%	
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.04%	0.07%	0.06%	
		0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.04%	0.47%	1.25%	8.22%
								0.03%	0.94%	2.86%	5.85%	29.32%

Figure 14. Relative head injury cost map for adult male pedestrians (hypothetical output)

								0.69%	7.28%	8.15%	5.61%	9.26%
		0.00%	0.00%	0.00%	0.01%	0.01%	0.07%	0.23%	0.61%	2.57%	2.43%	5.46%
	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.03%	0.23%	0.61%	0.54%	0.23%	
	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.03%	0.11%	0.61%	0.54%	0.23%	
	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.03%	0.11%	0.61%	0.54%	0.23%	
	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.02%	0.11%	0.61%	0.54%	0.23%	
	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.02%	0.11%	0.30%	0.16%	0.23%	
0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.02%	0.03%	0.30%	0.16%	0.23%	
	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.03%	0.11%	0.30%	0.16%	0.23%	
	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.03%	0.11%	0.61%	0.54%	0.23%	
	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.07%	0.11%	0.61%	0.54%	0.23%	
	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.03%	0.11%	0.61%	0.54%	0.23%	
	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.07%	0.23%	0.61%	0.54%	0.23%	
		0.00%	0.00%	0.00%	0.01%	0.01%	0.07%	0.23%	0.61%	2.57%	2.43%	5.46%
								0.69%	7.28%	8.15%	5.61%	9.26%

Figure 15. Relative head injury cost map for adult female pedestrians (hypothetical output)

								1.76%	4.89%	3.93%	2.56%	5.16%
		0.23%	0.37%	0.49%	0.96%	0.59%	0.97%	0.81%	0.79%	1.51%	1.14%	2.63%
	0.12%	0.23%	0.37%	0.49%	0.56%	0.59%	0.58%	0.81%	0.79%	0.44%	0.17%	
	0.12%	0.23%	0.37%	0.18%	0.22%	0.59%	0.58%	0.49%	0.79%	0.44%	0.17%	
	0.12%	0.07%	0.12%	0.18%	0.22%	0.59%	0.58%	0.49%	0.79%	0.44%	0.17%	
	0.04%	0.07%	0.12%	0.18%	0.22%	0.59%	0.25%	0.49%	0.79%	0.44%	0.17%	
	0.04%	0.07%	0.12%	0.18%	0.22%	0.25%	0.25%	0.49%	0.48%	0.19%	0.17%	
0.47%	0.04%	0.07%	0.12%	0.18%	0.22%	0.25%	0.25%	0.21%	0.48%	0.19%	0.17%	
	0.04%	0.07%	0.12%	0.18%	0.22%	0.59%	0.58%	0.49%	0.48%	0.19%	0.17%	
	0.04%	0.07%	0.12%	0.18%	0.22%	0.59%	0.58%	0.49%	0.79%	0.44%	0.17%	
	0.12%	0.07%	0.12%	0.18%	0.22%	0.59%	0.97%	0.49%	0.79%	0.44%	0.17%	
	0.12%	0.23%	0.37%	0.18%	0.22%	0.59%	0.58%	0.49%	0.79%	0.44%	0.17%	
	0.12%	0.23%	0.37%	0.49%	0.56%	0.59%	0.97%	0.81%	0.79%	0.44%	0.17%	
		0.23%	0.37%	0.49%	0.96%	0.59%	0.97%	0.81%	0.79%	1.51%	1.14%	2.63%
								1.76%	4.89%	3.93%	2.56%	5.16%

Figure 16. Relative head injury cost map for child pedestrians (hypothetical output)

Appendix 2: Definitions of False Positive activation

Safety systems may or may not be activated, and this activation may or may not have been called for. Therefore, safety system activation can be interpreted as a traditional classification problem with combinations of *target* ("was activation called for?") and *classification* ("was the system activated?") as illustrated in Table 6.

Table 6. Classifier evaluation. Traditional definition adopted from Martinez and Martinez (2008) on white background, addition from Otubushin (2011) on grey background

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Classification</td></tr>
<tr><td>Yes</td><td>No</td></tr>
<tr><td rowspan="3">Target</td><td>Yes</td><td>True Positive</td><td>False Negative</td></tr>
<tr><td rowspan="2">No</td><td>Near Miss</td><td rowspan="2">True Negative</td></tr>
<tr><td>False Positive</td></tr>
</table>

More specifically, the traditional classification problem defines the four outcomes as follows:

- True Positive: A target case is correctly classified as target
- False Positive: A non-target case is incorrectly classified as target
- True Negative: A non-target case is correctly classified as non-target
- False Negative: A target case is incorrectly classified as non-target.

Interpretations and modifications have been proposed to make use of the classification scheme in pedestrian safety research which are discussed below.

Helmer (2014) interprets the traditional classification for active safety systems aiming to protect pedestrians such that *classification* is defined as *system action* and *target* as *dangerous situation.* An unambiguous definition especially of the *target*, was not achieved; a footnote adds that "no generally accepted or universally applicable definition of 'dangerous' exists". False Positive activation is therefore defined as the system acting as if in a hazardous situation while objectively being in a non-dangerous situation.

Otubushin *et al*. (2011) note that "near miss" False Positive activation might be acceptable to drivers, and introduced "near miss" as a fifth category to the traditional classification. Najm *et al*. (2006) defined "near crash" which appears to refer to the same situation as "near miss" in Otubishuin (2011). A "near crash" is a situation requiring hard steering or braking at the last second. The difference between a "near miss" or "near crash" and a "dangerous situation" is not obvious, and the definition therefore remains vague.

Lees and Lee (2008) categorise warnings in the three dimensions: *Performance*, *process* and *purpose*. *Performance* describes the objective ability of the system to aid the driver, rated as "useful" or "nonuseful". *Process* describes the systems operation in respect to the subjective expectation of the driver, rated as "predictable" or "unpredictable". *Purpose* describes the systems operation in relation to the designer's objectives and is rated as "intended" or "unintended". Systems falling into the different categories and the consequences are described in Lees and Lee (2008).

Källhammer *et al*. (2014) noted that an ex-post definition regarding the occurrence of a collision event is problematic since successful system intervention – preventing a collision – turns out to be a False Positive intervention. False Positive definitions reviewed were ambiguous but congruous in that the usefulness of an alarm, dependent on context and driver perception, is more important than its classification as true or false.

Active safety system activation aims at avoiding collisions or mitigating their severity. Thus, it seems opportune to define *target* in relation to the occurrence of a collision. A simple definition based on a collision event ex-post as *target,* however, would not take any collision avoidance due to an activation of an active safety system into account. An event in which an effective system succeeded in avoiding a collision would be classified as a False Positive activation, while an event in which a less effective system, activated under the exact same circumstances, failed to avoid a collision would be classified as a True Positive activation. Thus, I propose that a better basis for the definition of *target* is to reference the time of system activation rather than subsequent events or outcomes. *Target* could be defined as the certainty of a collision without system activation at the time of system activation. It is assumed that the probability of a collision, thus also the certainty, can be calculated objectively.

For these *target* cases, i.e. those cases where a collision without system intervention is certain at the time of system intervention, interpretation of corresponding *classification* seems straight forward. System activation - that is True Positive activation - is intended, predictable, and useful. No system activation - False Negative activation - is untended, unpredictable, and nonuseful. There is little reason to believe that any stakeholder would prefer a system not to activate in this situation for the system to work as intended, which is to avoid collisions or mitigate their severity.

True Negative and False Positive definitions need deeper consideration.

Källhammer (2011) argues that since collisions, and consequently True Positive alarms are rare, drivers will not be able to react efficiently to an alarm. It is suggested that it is better not to attempt to eliminate all false alarms, but to design them to be meaningful with respect to driver acceptance. False alarms may not only be acceptable but even required for the system to be able to aid the driver. This links *Process* and *Performance.* A “predictable” and meaningful False Positive activation makes a system “useful”. Following this argument, False Positive activation is separated into “useful” and “nonuseful” in Table 7.

True Negative activation also needs to be further divided into “predictable” and “unpredictable” from the perspective of driver acceptance. As Abe and Richardson (2006) note, drivers might expect an alarm in a certain situation where a collision is still avoidable, do not get it, conduct an evasive manoeuvre, and perceive the True Negative event as a False Negative. These True Negative but “perceived false alarms” (Wheeler *et al*., 1998) lead to reduced trust in the system. Thus, the “predictable” system that meets driver expectations will turn into a “useful” system and the “unpredictable” system will turn into a “nonuseful” system as categorized in Table 7.

Table 7. Active Safety system activation evaluation scheme. “Useful” activation on grey background, “nonuseful” activation on white background.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">System activation</td></tr>
<tr><td>Yes</td><td>No</td></tr>
<tr><td rowspan="3">Collision certain without system activation?</td><td>Yes</td><td>True Positive</td><td>False Negative</td></tr>
<tr><td rowspan="2">No</td><td>Useful
False Positive</td><td>Useful
True Negative</td></tr>
<tr><td>Nonuseful
False Positive</td><td>Nonuseful
True Negative</td></tr>
</table>