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Integrated Pedestrian Safety Assessment Methodology

NILS LÜBBE

Department of Applied Mechanics
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Department of Applied Mechanics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31 772 1000

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Integrated pedestrian safety assessment methodology

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

Abstract

Pedestrian fatalities and injuries are a concern in many regions. Passive safety assessment is well established, and additional active safety assessment has recently emerged. However, assessment methods reflecting on the interaction between active and passive safety do not exist in regulatory or consumer testing. An integrated safety assessment that takes consideration to the information gained by active safety evaluation and modifies the passive safety assessment accordingly is needed to reduce pedestrian casualties effectively and efficiently. Such an assessment can guide the development and proliferation of vehicles offering the greatest benefit in terms of total safety offered.

The goal of this thesis is to contribute to the development of an integrated pedestrian safety assessment methodology. Firstly, conceptual work identifies key issues and a way forward for the assessment of True Positive performance, which is predicted injury reduction in test conditions in which safety systems are to be activated.

Secondly, False Positive test procedures are considered to provide guidance on balancing between True Positive performance and False Positive driver annoyance (activation of automatic emergency braking of forward collision warnings in test conditions in which safety systems are not meant to activate leading to driver mistrust and switched-of systems). To do so, driver comfort zone boundaries for pedestrian crossing situations are quantified indicating the transition point from normal situations to uncomfortable driving situations in which the driver will take corrective action. This data can be used to differentiate between *desired* and *undesired* False Positive activation, which in turn can help in designing False Positive test procedures.

A concept for the development of an integrated pedestrian safety assessment methodology is presented in Paper I. Further work is needed to collect data to facilitate the design of a usable and accurate assessment method from this concept.

Comfort zone boundaries for pedestrian crossing situations were quantified in Papers II and III. Time-To-Collision (TTC) had comparably low variation in the driver population in two complimentary studies on both a test track and in a driving simulator. The comfort zone boundary TTC was independent of the car's travelling speed but depended on pedestrian crossing speed. The 90 percentile value for TTC at the comfort zone boundary for 1 m/s pedestrian speed was 2.5 s in Paper II and 2.6 s in Paper III. The value for pedestrian speed of 2 m/s was 2.2 s TTC identified in Paper III.

The methodology as suggested in this thesis relies on the testing of active safety systems in representative scenarios, and testing of passive safety with impactor tests. Thus, any limitations with the test procedures for active and passive safety, such as unrealistic reflectivity of test targets or lack of biofidelity of impactors, will have its impact on the integrated methodology.

Keywords: pedestrian, assessment, integrated safety, False Positive, Forward Collision Warning, driver behavior, comfort zone boundary

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. 761-65, 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
Lubbe N, Rosén E. Pedestrian crossing situations: Quantification of comfort boundaries to guide intervention timing. *Accident Analysis and Prevention*, Vol.71, pp.261-66, 2014.
Division of work between authors: Rosén and Lubbe jointly designed the study. Lubbe analyzed and presented the data. The paper was written by Lubbe and reviewed by Rosén.

Paper III
Lubbe N, Davidsson J. Drivers' comfort boundaries in pedestrian crossings: a study in driver braking characteristics as a function of pedestrian walking speed. *Manuscript*
Division of work between authors: Lubbe outlined this study. Lubbe analyzed and presented the data. The paper was written by Lubbe and reviewed by Davidsson.

Definitions and Acronyms

ADAC	Allgemeiner Deutscher Automobil Club, a German motorist organization
AEB	Automatic Emergency Brake
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 Experimental Vehicle Committee
Euro NCAP	European New Car Assessment Program
FE	Finite Element
GIDAS	German In Depth Accident Study
HARM	A monetary measure of human and material crash harm
ISS	Injury Severity Scale
ITARDA	Institute for Traffic Accident Research and Data Analysis
JMLIT	Japanese Ministry of Land, Infrastructure, Transport and Tourism
JNCAP	Japanese New Car Assessment Program
MAIS	Maximum Abbreviated Injury Scale
NHTSA	National Highway Traffic Safety Administration
PCM	Pre-Crash Matrix
PMHS	Post Mortem Human Subject
PreEffect-iFGS	Assessment method Predicting Effectivness of ingetrated Fußgängeschutzsysteme (German for pedestrian protection systems)
Rpmi	Risk of permanent medical impairment
RSC	Rating System for Serious Consequences
STRADA	Swedish Traffic Accident Data Acquisition
TTC	Time to Collision, calculated as velocity divided by distance
VERPS	Vehicle Related Pedestrian Safety
vFSS	Advanced Forward-Looking Safety Systems, a consortium for developing AEB test procedures
VRU	Vulnerable Road User, defined as pedestrians, cyclists and motorized two-wheelers

1) Introduction to pedestrian safety

a) *Epidemiology (accident and injury types)*

Pedestrian fatalities and injuries are a concern in many regions that needs 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 with 35% (ITRADA, 2012).

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

A majority of pedestrian fatalities occur in darkness: 51% in the EU 2010, 70% in the USA 2012 and 69% in Japan 2009 (Pace et al., 2012; NHTSA, 2014; ITARDA, 2011). Considering not only fatal, but also seriously injured pedestrians, a 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 injury severity under consideration. Wisch et al. (2013) developed 6 distinct accident scenarios with weighting factors (proportion of the scenario compared to all accidents at the specified injury severity “Killed and Severely Injured (KSI)”, “Fatality” and “All Casualities”) for Europe as presented in Fig. 1. Fig. 1 accounts for about 50% of all accidents involving pedestrians; additional scenarios account for the remaining portion of accidents. For the USA, Yanagisawa et al. (2014) indicated 4 priority scenarios. Fig. 2 depicts these scenarios with corresponding fatality rates.

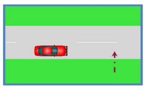
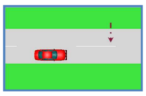
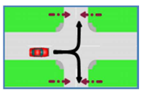
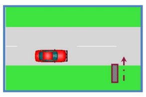
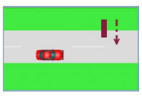
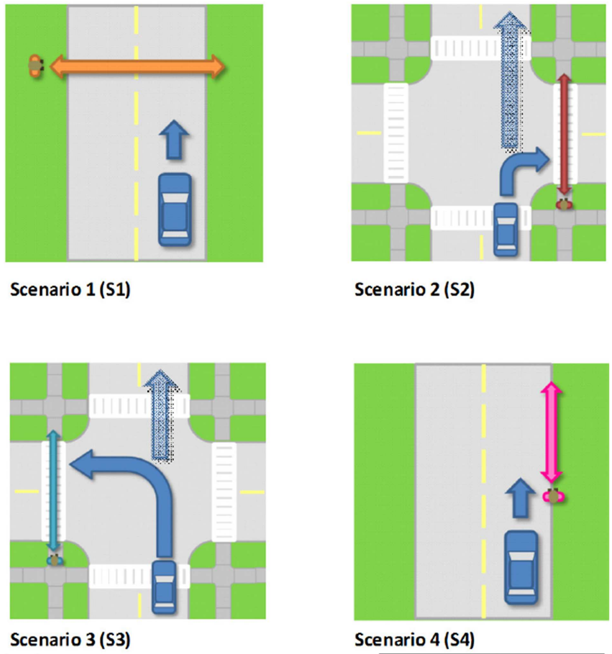
ID	AccScen Categories	Description	EU-27 Weighting Factors		
			KSI	Fatalities	All casualties
1		Crossing straight road, near-side, no obstruction	15%	13%	11%
2		Crossing straight road, off-side, no obstruction	12%	17%	9%
3 & 4		Crossing at junction, near- or off-side, vehicle turning or not across traffic	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%

Fig. 1: European accident scenarios adopted from Wisch et al. (2013)



		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%

Fig. 2: US accident scenarios Yanagisawa et al. (2014)

Looking at in-depth studies of injuries sustained in pedestrian accidents the importance 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 German GIDAS data (Liers and Hannawald, 2009; Liers, 2010; Fredriksson et al., 2010), the French Rhône Trauma Registry (Martin et al., 2011) and US CIREN data (Mueller et al., 2012). Exact numbers differ with study design as depicted in Fig. 3. 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, regions and injury severity studied. Studies at different injury severities measured according to the Abbreviated Injury Scale (AIS) are presented in Fig.3. 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.

With increasing injury severity, head injuries gain importance, and 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).

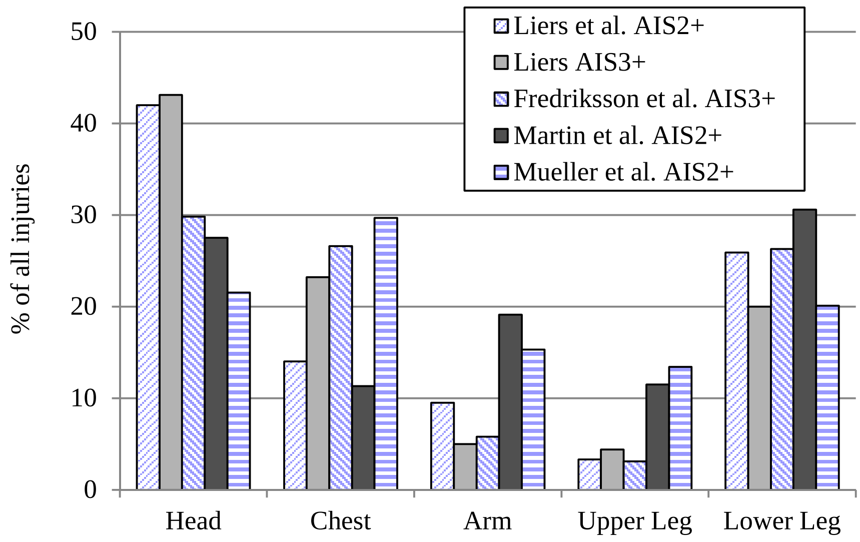


Fig. 3: Injury frequency by body region

b) Possibilities for protection of pedestrians

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 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, and safe crossing facilities. Education can improve skills and behavioral patterns. Vehicle design plays a role for those collisions where a vehicle is the collision partner of a pedestrian. Design measures may include energy absorbing car fronts, and under-run protection on trucks (Wittink, 2001). Detailed descriptions on how vehicle design can be modified to improve predicted pedestrian protection can be found, for example, in Bachem (2005) and Lawrence et al. (2006) focusing on passive safety, that is, design of energy absorbing structures to mitigate injury outcome during the collision and contact phases, or Fredriksson (2011) exploring passive and active safety impact, thereby also including technology for impact speed reduction prior to a collision. This thesis focuses on the assessment of such pedestrian protection offered by active and passive safety systems of vehicles.

More precisely, the aim is to assess passive safety as the ability of 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) and active safety as the ability of systems to reduce speed prior to a collision, including automatic 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 at reducing the number and severity of collisions by supporting the driver when no collision is imminent, such as fatigue monitoring or night vision enhancement. Further, systems that do not aim at reducing speed prior to impact but instead at avoiding collisions by other means are not within the scope of the thesis. An example for such technology is automatic steer avoidance, aiming at steering around a potential collision partner (Toyota, 2013). Speed reduction and other technology seems to be fundamentally different, as speed reduction is likely to mitigate injury outcome even if the collision cannot be avoided altogether (the possibility of changing impact location and increasing probability of injury will be discussed later) while the mitigation potential of, for example, “partial” steer avoidance, that is, steering but not avoiding a collision, is less obvious.

c) *Assessment of pedestrian safety offered by vehicles*

There are many ways of assessing pedestrian protection offered by vehicles: a first categorization can be made depending on whether protection is studied retrospectively on real-world data or predicted in a prospective study design.

Real-world data and accident research in retrospective studies can provide general trends, such as reduction of pedestrian fatalities compared to other modes of transport. Effects of safety systems widely employed in the vehicle fleet can also be studied in terms of accident avoidance and injury mitigation. Assessment of pedestrian protection for a single vehicle model is generally not possible due to scarce data, or at least not available until several years after market introduction.

Test methods for predicting pedestrian safety can be categorized according to the type of test object impacting the vehicle: Schmitt et al (2004) proposed five categories: Human volunteers, human cadavers (Post Mortem Human Subject, PMHS), animals, mechanical human surrogate models and mathematical models. For pedestrian safety assessment, mechanical human surrogate models and mathematical models are in use, and briefly discussed below. Mechanical human surrogate models are further divided in subsystem hardware impactor, representing a specific body region and full body representation. Further, safety assessment is divided into the collision phase being studied: Active safety for reduction of collision probability and/or collision severity so that injury probability 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 passive safety, 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 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 aiming at predicting 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, and is the topic of this thesis.

i. Retrospective assessment

Assessments of the protection of car occupants offered by specific vehicles in retrospective studies have been established and are presented, for example, in Hautzinger (2006). The Folksam crash safety rating for passive occupant safety is published biannually on their website (Folksam, 2013). For pedestrian protection, a retrospective study to rate specific vehicles was concluded (Delaney et al., 2006), but no recent ratings are available.

The effects of safety devices are difficult to establish since vehicles hardly ever differ in only one specific feature. For example, one might want to establish the effect of an active hood. A vehicle with an active hood might create additional deformation room when deployed and thus reduce injury probability compared with the same car with an undeployed active hood. However, the same car is hardly ever equipped both with and without an active hood. The benefit will only be evident comparing the same car (the same under bonnet clearance) with and without an active hood. Comparing vehicles with an active hood in general against vehicles without this device might not reveal any safety effect, since those vehicles that do not create additional deformation room through bonnet deployment might provide exactly the same amount of deformation room as the deployed bonnet through a different design, without the need for deploying the hood. To study the benefit of an active hood, one might need to stratify for deformation space prior to deployment, which seems to be a rather complicated endeavor. Hypothesized to relate to available deformation space, Pastor (2013) found engine size to have an effect on pedestrian protection: The larger the engine, the higher the probability of injury. This example of an active hood illustrates how confounding factors complicate establishing safety benefits for specific technology. Having firmly established benefit (see for example Rizzi et al., 2014 on car-to-car AEB benefits), one could advertise such beneficial technology and ensure that assessment methods reflect this benefit in their scoring systems.

Retrospective assessment requires data from past collisions to be accessible. For a specific car model, sufficient data may not be available until years after its introduction, if available at all, depending on sales volume and number of reported incidences. Thus, prospective assessment methods appear better suited to establish pedestrian protection offered by new cars, which is the focus of this thesis. Still, retrospective analyses have an important role to play for prospective assessment. Past predictions of protection offered by cars need to be validated against real-world accident data of collisions that occurred with these cars to ensure that prospective assessment measures relevant safety improvements.

The Euro NCAP pedestrian rating has been used as an indicator for overall protection provided by a vehicle in relation to real-world injury outcome. Vehicles with a high star rating were found to be associated with a lower probability of injury risk (Strandroth, et al., 2011; Pastor, 2013). Even though Liers (2009) noted that “vehicles with equal Euro NCAP pedestrian ratings (point scores) may have great as well as small real-world benefits”, the Euro NCAP pedestrian score is an important indicator, and currently the only property of a vehicle in respect to pedestrian protection used in the Swedish requirement for state operated cars (SFS, 2009) and Folksam’s new car buyer recommendations (Folksam, 2014).

ii. Prospective Assessment

1. Passive Safety

Regulation and consumer testing is conducted with subsystem hardware impactors: A physical model of an adult's head, a child's head, a lower leg and an upper leg impacts the vehicle under assessment. Notably, a chest impactor is not in use, while the chest is among the most commonly injured body regions (see section 1.a). An overview on procedures can be found in Carhs (2014). Details on test procedures can be found in EEVC (2002), Euro NCAP (2013a); Euro NCAP (2013b); 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, and is usually debated for each test. Biofidelity has been particularly questioned for the European Enhanced Vehicle-Safety Committee (EEVC) Working Group (WG) 17 upper leg test (EEVC, 2002) (Cesari, 2008; Hamada et al., 2005; Snedeker et al., 2003).

Subsystem hardware impactor tests have the advantage of being repeatable (Lawrence, 2005), but 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). 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. 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 rigid 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, thus can be faster and less costly than testing with physical models or PMHS. As for hardware tests, the validity of a test depends on biofidelity regarding impact kinematics and injury assessment. The Total Human Model for Safety (THUMS), an FE full human body model in its latest Version 4 has been validated to some extent (Watanabe et al., 2012) 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, 2013b). 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 focuses on the assessment of passive safety using subsystem hardware impactors.

2. Active Safety

Collision speed has a major influence on pedestrian injury probability, the relationship has been established independently from different datasets (Davis, 2001; Rosén and Sander, 2009; Rosén et al., 2010; Tefft, 2011). Active safety for current pedestrian protection mainly concerns systems warning the driver of an imminent collision, and applying brakes automatically 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 scores against desired speed reduction (Euro NCAP, 2014; AEB Group, 2011; Niewöhner et al., 2011, ADAC, 2014).

In current assessments, tests are 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 (Lemmen et al., 2013). In most assessment schemes (Euro NCAP, 2014; AEB Group, 2011; ADAC, 2014) only speed reduction performance of the automatic braking is assessed. Only vFSS (2012a) developed a protocol to assesses the speed reduction achieved by a warning system. A driving robot brakes after a warning is issued, and 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 to the speed reduction achieved. Euro NCAP plans to rate warnings given prior to 1.2 s Time To Collision (TTC) as positive (Euro NCAP, 2014). Also, ADAC rates system warnings, but the criteria are unclear (ADAC, 2014). Technologies such as steer avoidance (Toyota, 2013) or adaptive illumination (systems that increase night time visibility by adapting the illumination area to road geometry "curve light", systems that adapt to other traffic participants by automatically balancing illumination strength and glare, or systems that adapt to hazard levels by indicating imminent or potential collision objects with a spotlight) are currently not assessed. Further research is needed for the assessment of systems not aiming at automatic speed reduction, such as warnings, steer avoidance and adaptive illumination. As warning systems are already available on the market, the need to develop quantitative assessment procedures reflecting real-world benefit in injury reduction is urgent.

Seiniger et al. (2013) defined desired speed reduction by what is thought to be technically feasible, and developed a simulation environment to allow virtual testing of systems in specific collision scenarios. Various approaches for simulation of active safety systems for pedestrian protection have been developed. These might be classified according to the data used to create traffic situations to be studied for the effect of active safety systems.

The first approach, *single accident reconstruction*, relies on a description of the traffic environment and the paths travelled by vehicle and pedestrian in collisions provided by a database, such as the German Pre-Crash Matrix (PCM) Erbsmehl (2009). Each of these accidents is then reconstructed in a simulated environment allowing replication of the accident with and without the active safety system under study, and established the comparative impact a system has on the collisions. The active safety system is usually a simplified model of the real system including sensors, logic and actuation. This approach has been successfully employed, for example, by Rosén (2013) using PCM data and Anderson et al. (2012a) using in-depth data collected by the Australian Centre for Automotive Safety Research.

The second approach, *traffic simulation*, creates paths of the vehicle and pedestrian from characteristic parameters of the traffic environment or accident data. Thus, both accidents and non-accident situations are simulated. Regions for which databases with pre-crash paths are not available can be simulated, which enables an analysis of the impact of active safety technology 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.a) and the active safety system including sensors, logic and actuation. While simulation approaches are appealing in terms of the simplicity of obtaining results, once the model is validated, it is challenging to establish model validity. Use in regulation and assessment 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, similar to passive safety, is not expected to be widely applied in regulatory and consumer assessment of pedestrian protection within the near future.

Active safety assessment is a field in rapid development consisting of divergent methods. Most approaches measure only speed reduction. Passive safety assessment, on the other hand, commonly measures impactor responses and relates them to injury probability. Further research is needed to define a common metric for vehicle specific assessment of active and passive safety features, and to model interaction between active and passive safety features such as the shift of impact location with reduced speed and its consequences for injury probability noted, for example, by Matsui et al. (2011) and Watanabe et al. (2012). A truly integrated safety assessment can only be obtained when modeling this interaction.

3. Integrated safety

While passive safety assessment is well established in regulation and consumer testing, active safety system assessment has only recently emerged. Using a systems perspective of the road transport system, an integrated safety approach is needed to reduce pedestrian casualties effectively and efficiently. Yet, integrated safety assessments – assessments that take into account information gained by an active safety functionality evaluation and modify the passive safety assessment accordingly, are not applied in regulatory or consumer testing. Some integrated assessments based on computer simulations have been proposed (e.g. Kompass, 2012; Seo et al., 2014). Assessments incorporating the established subsystem hardware impactor tests, such as a leg impactor test, seem to be more likely to be adopted in regulatory and consumer testing, and are presented in the following subsections.

a. VERPS

An early method for integrated safety assessment, the so-called "Vehicle Related Pedestrian Safety - index" (VERPS-index), has been proposed by Kühn et al. (2005), Kühn et al. (2007) and was further developed by Hamacher et al. (2011) and Hamacher et al. (2013). 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 features.

The VERPS-index was originally defined as follows: For a given accident scenario impact areas 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).

To assess the benefit of active safety devices, an impact speed of 40 km/h is assumed and tested. Impactor responses at additional test speeds (20, 30, 35 km/h) are estimated to approximate the effect of active safety speed reduction on the impactor response. Injury probability is calculated for impact speeds after an active safety intervention. Thus, kinematic changes due to impact speed reduction can be included. Final results are weighted for different accident scenarios with their respective speed and injury reduction. Further, a separate index for lower leg protection is added to the assessment following the same logic as for the head (Hamacher et al., 2013).

While this integrated method brought forward the idea of vehicle specific impact point distribution together with component testing, it has several limitations. This 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 technology. That means that injuries at lower injury severity are not explicitly considered (AIS2 risk might however correlate with AIS3+ risk) and, more importantly, that no further differentiation of high to maximum severity takes place. The risk curves presented reach a 100% probability of an AIS3+ injury at an HIC of approximately 2500. Thus, a reduction from HIC 5000 to 3000 will indicate no benefit at an AIS3+ level, while some benefit can be expected for the highest severity injuries (Injury risk curves e.g. from NHTSA, 1995 or Matsui, 2004). Further, the method does not assess body regions other than the head and lower leg, and does not combine results. Furthermore, the calculation of the index is conducted at one test speed only (which may or may not be reduced by active safety systems), which is derived from accident data, but cannot account for trade-offs between different test speeds. Finally, uncertainty is not explicitly modeled.

Searson et al. method

This assessment method focuses on evaluating pedestrian safety for head impact at all possible impact speeds (Hutchinson et al., 2012; Searson et al., 2012a). Impact frequencies are 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 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 impact speed distribution over which injury probability is aggregated according to reductions achieved by automatic emergency braking systems (Anderson et al., 2012b; Searson et al., 2014).

This method explicitly models the influence of both active and passive safety systems on head injury outcome. Further, the method accounts for trade-offs between different impact speeds. Therefore it can assess variations in pedestrian safety for speeds other than the test speed. However, some limitations exist. The test area is taken as externally defined, and kinematic changes due to active safety intervention have not been modeled. Body regions other than the head are not modeled, nor does the method model uncertainty.

b. PreEffect-iFGS

A method called PreEffect-iFGS to assess the combined effects of active and passive safety features for all body regions of a pedestrian has been described by Schramm (2011) and Roth and Stoll (2011) as depicted in Fig. 4.

The benefits of passive safety technology are calculated as the reduction in injury probability at a chosen maximum injury severity (MAIS) level compared to a reference car. The base passive safety performance is taken from Euro NCAP test results at one impact speed (40km/h). The reduction in injury probability for passive safety is calculated based on the "injury-shift method" developed by Liers and Hannawald (2009). Active safety benefit is assessed as the MAIS risk reduction obtained by the speed reduction estimated using simulation models. The corresponding risk reduction is calculated using global (not body region specific) injury risk curves from GIDAS. The outcome is the effectiveness of a combination of active and passive systems to reduce injury risk at a MAIS level.

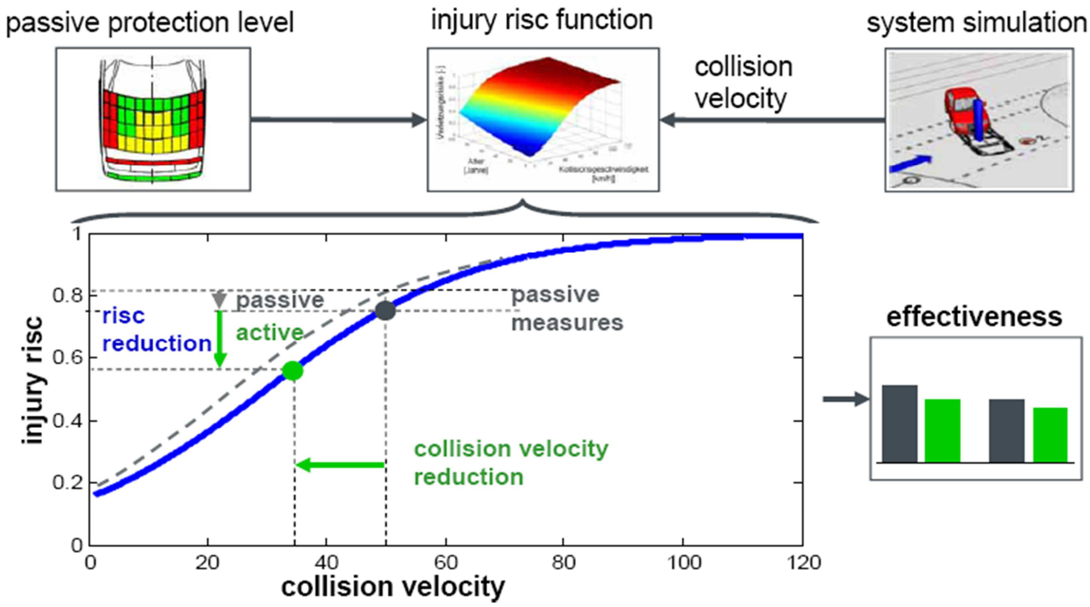


Fig. 4: Integrated pedestrian safety assessment methodology from Roth and Stoll (2011)

The main advantage of this method is that it covers several body regions; those currently being tested by Euro NCAP taking the relevance and impact point distribution as proposed by Euro NCAP. However this method also has its limitations. The choice of injury severity level and the 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 testing. The depicted injury risk curve (at MAIS2+ level) indicated a substantial injury risk at zero velocity, which is explainable from the data and method used but unlikely to accurately represent reality. As for the other methods, uncertainty is not explicitly modeled.

4. Outlook

There have been substantial changes to the assessment schemes for pedestrian safety in recent years, and there is no reason to believe assessments will become static in the future. New test tools, technology and priorities for society, among others, will continue to trigger updates and modifications to the assessment procedures.

JNCAP, for example, fundamentally modified their assessment of pedestrian safety in recent years. Starting with an assessment of the head only, a lower leg test was introduced in 2011 (JNCAP, 2013) and a rating for a pedestrian automatic emergency brake (AEB) is being considered for 2016 (JMLIT, 2014).

Euro NCAP also changed the test tools: The child headform impactor mass changed from an impactor with a mass of 2.5 kg to one with 3.5 kg in 2009. The lower leg impactor type is intended to change in 2014, and modifications to the upper leg impactor are planned for 2015 (Euro NCAP, 2013c). Further, test procedures were modified: A new way of defining impact locations, the grid procedure, was introduced in 2011. For active safety, a rating for Vulnerable Road User (VRU) AEB systems is scheduled for introduction in 2016 (Euro NCAP, 2013c).

An integrated safety assessment is needed to account for system interactions and reduce pedestrian casualties more effectively and efficiently. Protection, 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) have calculated the effectiveness of active and passive safety in a separated as well as in an integrated approach for severe head injury protection for pedestrians. This issue is certainly well known and not restricted to pedestrian protection. For example, Strandroth et al. (2012) addressed the problem of system interaction explicitly in a method for predicting the impact of future technology on road traffic fatalities involving passenger cars. By taking into consideration the fact that different technologies may address the same accident, the effectiveness of a combination of systems has been calculated studying each case individually, not assuming system independence.

An integrated safety assessment method is currently not on the agenda of consumer and regulatory testing, but is a part of research activities as described in section 1.c.ii.3 and the AsPeCSS project (Pla et al, 2014). Substantial future work is needed to develop an accurate and usable integrated assessment procedure for pedestrian protection offered by vehicles. This thesis aims at contributing to the development of such a method.

d) Safety system activation: Assessing False Positives

Assessment of safety systems mainly concerns itself with True Positive performance, which is, broadly speaking, the performance of a system activated (classification of the situation as requiring activation) in a situation in which activation was called for (target case). As described above, rating systems for these performances have been developed. Also False Negative activation, which is, put simply, a non-activation (classified as not calling for activation) for a target case, is naturally included in the ratings as no speed reduction will be achieved and no score will be given. Performances for non-target cases (activation not called for) have been less in the focus, but have recently been incorporated in the assessment methods of ADAC, vFSS and AsPeCSS. Before detailing these methods, a brief review of definitions for safety system activation is presented.

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 classification problem with the four combinations of target and classification (Fig. 5):

- True Positive (TP): A target case is correctly classified as target
- False Positive (FP): A non-target case is incorrectly classified as target
- True Negative (TN): A non-target case is correctly classified as non-target
- False Negative (FN): A target case in incorrectly classified as non-target

Classification			
Yes	No		
True Positive	False Negative	Yes	Target
False Positive	True Negative	No	

Fig. 5: Classifier evaluation (adopted from Martinez and Martinez, 2008)

Helmer (2014) gives a concrete example of a definition of active safety systems aiming at pedestrian protection. False Positive activation is defined as the system acting as if in a hazardous situation while objectively being in a non-dangerous situation. A footnote adds that “no generally accepted or universally applicable definition of ‘dangerous’ exists”. In Helmer (2014) *Classification* is defined as *system action* and *Target* as *dangerous situation.* An unambiguous definition especially of the *Target*, was not achieved.

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 classification scheme in Helmer (2014). Najm et al. (2006) defined “near crash” as a situation requiring hard steering or braking at the last second. The difference between a “near crash” and a “dangerous situation” is not obvious, and the definition therefore remains vague.

Källhammer et al. (2014) reviewed False Positive definitions in the broader context of automotive active safety systems. An ex-post definition regarding the occurrence of a collision event is regarded as 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.

Further, 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 has been suggested to not attempt eliminating all false alarms but design them to be meaningful with respect to driver acceptance. False alarms may not only be acceptable but even required. This indicates that further separation of the False Positive classification with categories *acceptable* or *required* is needed.

Clearly, a common and unambiguous definition of a False Positive pedestrian protection system intervention does not exist, and further research is needed for its application to integrated pedestrian safety assessment. In the following, methods of False Positive testing in current assessment methods are described.

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, thereby resolving the conflict situation independent 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 are unknown to me.

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, 2012b). 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 along with different tests for True Positive performance. Similar to the test procedure for True Positive performance, 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.

Three activation areas are identified 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 $3m/s^2$ and a safety distance assumed as 1m perpendicular to the driving path. 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” (Seininger et al., 2014). Table 2 in the discussion section gives the TTC threshold calculated for several scenarios calculated with the above assumptions.

Contrary to the procedure of ADAC described above, the amount of system activation was not discussed. 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. A differentiation between AEB and warning system thresholds was not presented by Seininger et al. (2014).

e) Concepts on comfort boundaries

Ljung Aust and Engström (2011) developed a framework for active safety evaluation, proposing the use of two boundaries: Firstly, a safety zone boundary, which divides states of maintained control and loss of control beyond recovery. Secondly, a comfort zone boundary, dividing states of a feeling of discomfort to the driver and a feeling of comfort (see Fig. 6). The difference between the two boundaries is the safety margin. Drivers aim at a state within the comfort zone and take corrective action when they exceed the boundary.

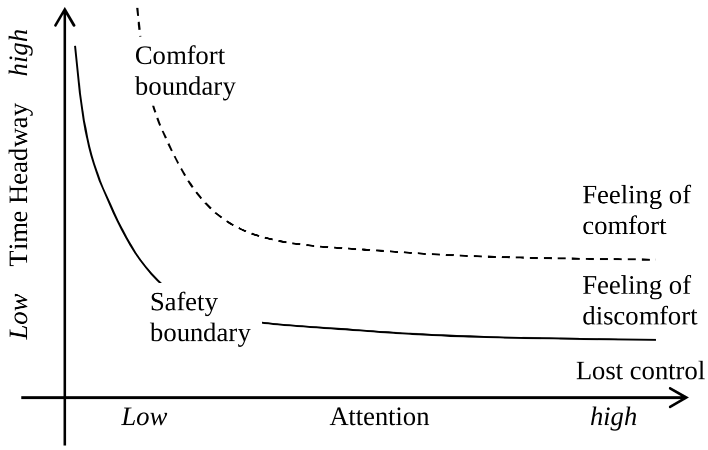


Fig. 6: Comfort boundaries adapted from Ljung Aust and Engström (2011)

The safety zone boundary is dependent on the road environment, driver capabilities, and expectancy, and is objective in the sense that it describes a physical limit. The comfort zone boundary consists of individual and subjective variations. Normally, individual estimates of comfort and safety zone boundaries ensure collision free driving. In some cases, however, when an individual estimate of the safety zone boundary is inaccurate, the comfort zone boundary may be too close to the safety zone boundary, or even exceed it. In case of the comfort boundary being too close to the safety zone boundary, active safety systems can aim at improving boundary perception. When the safety boundary is exceeded increased vehicle capabilities offer the possibility to regain control.

Finally, Ljung Aust and Engström (2011) illustrate intervention timing for different types of active safety systems:

1. Driver information in the comfort zone
2. Driver warning when nearing the safety zone boundary
3. Enhancing vehicle capabilities at the safety zone boundary to regain control
4. Enhancing vehicle capabilities to mitigate a collision (control is lost beyond recovery)

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 zone boundary is. If they do not however, the driver will regard the system's output as a nuisance and general source of irritation."

Comfort zone boundaries can be used to design a False Positive system test. This type of test can in turn guide the balance between True Positive system performance commonly assessed in current rating schemes and driver annoyance, which is of minor relevance in current assessment schemes. Quantification of comfort zone boundaries is essential and further research is needed.

2) Aims

The goal of this thesis is to contribute to the development of an integrated pedestrian safety assessment methodology. Firstly, key issues and concepts are identified. Secondly, comfort zone boundaries for pedestrian crossing situations are quantified to enable the design of a meaningful False Positive system activation test. This test, as part of an integrated assessment of the True Positive performance, can provide guidance for balancing True Positive system performance with False Positive driver annoyance to give the best overall result.

3) Definition of false positive activation in this thesis

False positive activations are relevant for both passive and active safety activation. For example, firing a pedestrian airbag (passive safety device when triggered by contact sensing) as well as activating automatic braking prior to a collision can be analyzed with the categories *Target* and *Classification*.

But the application of this classification to safety device activation is not as straightforward as it might seem, and some confusion might arise from improperly defined terms. *Classification* can be understood as "system activation", for example: "Has the pedestrian airbag been fired?" Or "Has automatic braking been activated?" Further complication arises if the classification is not binary, but the system allows for different levels of activation. For example, an active safety system might first warn the driver, then generate a gentle deceleration, and finally apply full brake force. Then, a classification into not only Yes/No but into Level1/Level2/Level3/No might seem necessary. However, this complication seems to be avoidable by defining the level of activation under consideration. For example, when defining "activation of a driver warning" as the system activation under consideration, one returns to a binary classification. Activation of a system is assumed to be measureable objectively.

Target could translate to *intended activation*. One could assume the target as a set of rules or situations specified by the system developer under which the system is intended or not intended to be activated. The differentiation into intended and not intended will be based on the specific aim of a particular system. Hence the same situation could be interpreted quite differently. With the aim of developing a cost-effective system, a developer making use of simple components might not intend to activate a system in a complex situation, while the aim of avoiding all collisions completely might lead to the intention to activate a system in nearly all situations imaginable.

In this thesis *Target* is defined for active safety activation. This definition calls for two new subjective subcategories based on driver acceptance as depicted in Fig. 7.

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 lack consideration of collision avoidance by active safety system activation. An effective system that succeeded in avoiding a collision would be assigned a false positive activation while a less effective system, activated under the exact same circumstances, not avoiding a collision would be assigned a true positive activation. Thus, it seems reasonable to reference the time of system activation for the definition of *Target* and not subsequent events. *Target* is 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.

Returning to *intended activation* there seems to be little doubt about the *Target* cases, i.e. those cases where a collision without system intervention is certain at the time of system intervention. True Positive activation is intended and False Negative activation is unintended. There is little reason to believe that any stakeholder would prefer a system not to activate in this situation given that the system works as intended, which is to avoid collisions or mitigate their severity.

True Negative activation needs to be further divided into *desired* and *undesired* 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 maneuver, and perceive the True Negative event as a false alarm. These True Negative but "perceived false alarms" (Wheeler et al., 1998) are undesired and lead to reduced trust in the system.

False Positive activation is further separated into *desired* and *undesired* from a driver acceptance perspective as called for by Källhammer (2011).

System activation			
Yes	No		
True Positive (TP)	False Negative (FN)	Yes	Collision certain without system activation?
Desired False positive (DFP)	Desired True Negative (DTN)	No	
Undesired False positive (UFP)	Undesired True Negative (UTN)		

Fig. 7: Active Safety system activation evaluation scheme. Desired classification on grey background, undesired classification on white background.

4) Summary of papers

a) *Summary of paper I: Towards an Integrated Pedestrian Safety Assessment Method*

INTRODUCTION. Some previous research has been performed to develop methodologies for assessing active and passive pedestrian safety systems, but to date no methodology has been developed which integrates these fully taking into account the effect of the active safety system on the passive safety system boundary conditions. This paper shows the principles for a fully integrated pedestrian safety assessment method. The main aim is to develop an assessment that is related to the benefit that the system will offer in real-world impacts.

METHODS. An integrated pedestrian safety assessment is being developed using literature review, accident data analysis, computer simulation, hardware testing and validation against real-world data. Key points considered are:

- A fully integrated assessment is necessary to assess relevant interactions of safety systems. Active safety intervention will influence passive safety performance. Impact kinematics might change resulting in a higher or lower predicted probability of injury.
- The methodology 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-optimization as the structure tested might not be developed to offer protection at higher 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 modeled.
- The influence active safety intervention might have on impact kinematics needs to be analyzed by full human body simulation and reflected in the methodology.

RESULTS. An outline assessment methodology has been developed. It consists 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 autonomous emergency braking 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 last 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 methodology, further substantial efforts are needed both to fill knowledge gaps and for validation.

b) Summary of paper II: Pedestrian crossing situations: Quantification of comfort boundaries to guide intervention timing

INTRODUCTION. Technical systems that warn or brake for vehicle - pedestrian encounters reduce injuries more effectively the earlier an intervention is initiated. However, premature intervention can irritate drivers, leading to system deactivation and, consequently, to no injury reduction whatsoever. It has been proposed that no intervention should be initiated as long as attentive drivers are within their comfort zones. This study aims at quantifying driver comfort boundaries for pedestrian crossing situations to offer guidance for the appropriate timing of interventions.

METHODS. Sixty-two volunteers drove through an intersection on a test track at 30 and 50 km/h. A pedestrian dummy was launched from behind an obstruction towards the driving path of the approaching car. Brake onset indicated discomfort. Time to collision (TTC), longitudinal and lateral distance were measured at brake onset.

RESULTS. TTC was independent of driving speed ranging from 2.1 to 4.3 s with a median of 3.2 s. Longitudinal distance ranged from 19 to 48 meters with an apparent difference between driving speeds. Lateral distances differed slightly, but significantly between driving speeds. The median was 3.1 m (3.2 m for 30 km/h and 2.9 m for 50 km/h) and values ranged from 1.9 to 4.1 m. Lateral distance in seconds ranged from 1.9 to 4.3 s with a median value of 3.1 s (3.2 s for 30 km/h and 3.0 s for 50 km/h).

DISCUSSION. TTC was independent of driving speed, trial order and volunteer age. It might be considered suitable to intervene in situations where, for example, 90% of drivers have exceeded their comfort boundary, i.e. when drivers have already initiated braking. This percentile value translates to intervention at a TTC of 2.5 s independent of driving speed as depicted in Fig. 8 together with all test data. The study was limited to Swedish nationals, fully aware drivers, and two driving speeds, but did not investigate behavioral changes due to system interaction.

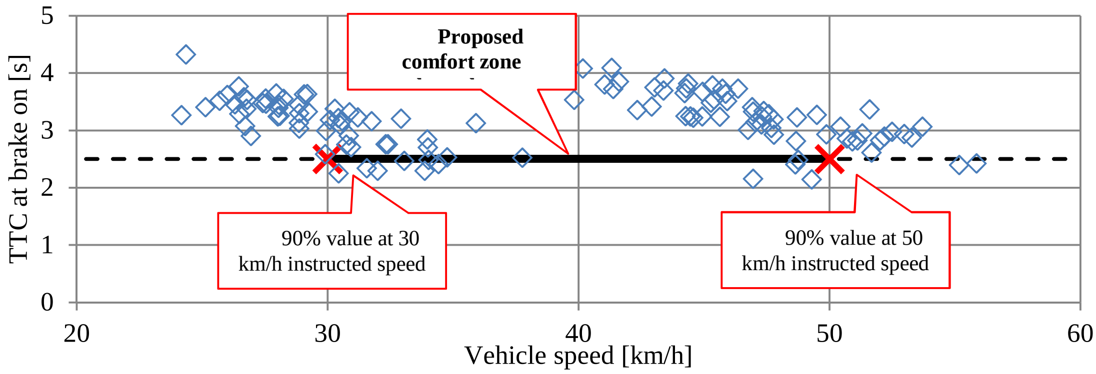


Fig. 8: Proposed comfort zone boundary for False Positive assessment independent of vehicle speed

CONCLUSION. This study showed that TTC at brake onset was a suitable measure for the quantification of driver comfort boundaries in pedestrian crossing situations. All drivers applied their brakes prior to 2.1 s TTC.

c) Summary of paper III: Drivers' comfort boundaries in pedestrian crossings: a study in driver braking characteristics as a function of pedestrian walking speed

INTRODUCTION. Technical systems that inform or warn the driver of an imminent collision or automatically initiate braking have been entering the market. One of the major challenges is to balance system performance in collisions against the possibility of undesired system activation. The distinction between desired and undesired system activation can be based on driver discomfort. This study focuses on the dependency of TTC at brake onset on pedestrian speed.

METHODS. The influence of pedestrian speed on brake onset as the measure for comfort boundaries, brake reaction times and brake deceleration levels were investigated in a high-fidelity driving simulator in Japan. Naive volunteers drove at 30 km/h in an urban environment and were subjected to two pedestrian crossing situations at 1 m/s and 2 m/s pedestrian speed resulting in 188 measurements of brake onset.

RESULTS. The 90-percentile values were 2.6 s TTC for 1 m/s pedestrian speed and 2.2 s TTC for 2 m/s, 19 m longitudinal distance for 1 m/s pedestrian speed and 21 m for 2 m/s, 2.7 m and 2.7 s lateral distance for 1 m/s pedestrian speed and 4.5 m and 2.3 s for 2 m/s. The reaction times of the volunteers in this study were no longer than the ones reported in similar test track studies. Thus, the test track study for Paper 2 appears to be unbiased towards fast reactions. Volunteers applied brakes at an average deceleration level of 3.8 m/s2, and a brake jerk of 3.7 m/s3, and tended to adjust their deceleration levels downwards over time.

DISCUSSION. Using, for example, 90-percentile values of brake onset TTC allows setting a differentiating threshold between desired and undesired intervention in pedestrian crossing situations. It should be noted that the threshold to differentiate desired from undesired system intervention was suggested to be independent of car speed in the range of 30 to 50 km/h (Paper II) and was found to be dependent on pedestrian speed in this driving simulator study (Fig. 9). Further influencing factors, for example light and road conditions, may exist.

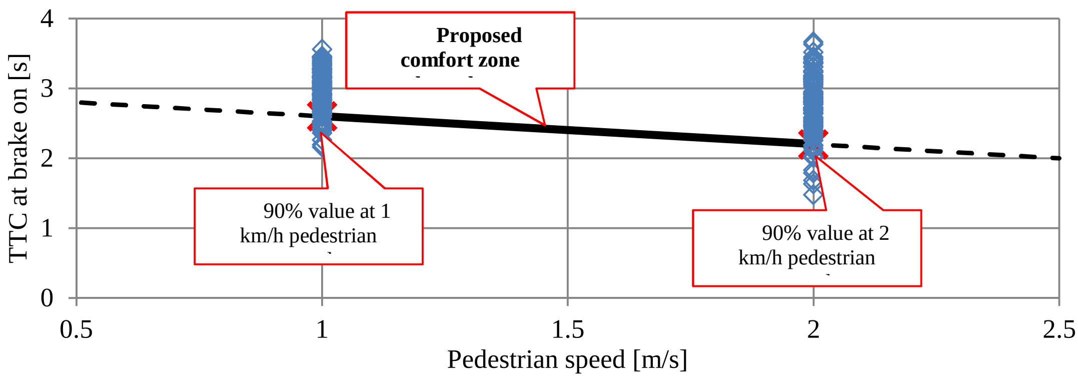


Fig. 9: Proposed comfort zone boundary for False Positive assessment dependent on pedestrian speed

CONCLUSION. Pedestrian speed was found to have a significant influence on brake onset. For pedestrians at 1m/s, 90% of drivers braked before 2.6 s TTC. For 2m/s this value was 2.2 s TTC. These values might guide differentiation between desired and undesired intervention in the design of an "unjustified system response" test in the assessment of pedestrian safety from a driver behavior perspective. An intervention prior to these times in false positive pedestrian crossing scenarios might be considered too early and therefore undesired.

5) General discussion

Pedestrian casualties are a concern in many regions due to their considerable proportion of road traffic casualties. Not only the resulting totals, but current reduction rates as well highlight the need for further efforts in pedestrian protection. While car occupant fatalities have been receiving much attention, and have been reduced in EU-19 by 50% in 2010 compared to 2001, pedestrian fatalities have been reduced by only 39% (Pace et al., 2012; Candappa et al., 2012). Car occupants remain the dominant group of road traffic fatalities, but their proportion decreased from 55% to 48% from 2001 to 2010 (Fig. 10), while for pedestrians the propotion of all road traffic fatalities has not been reduced remaining at approximately 19% (Pace et al., 2012; Candappa et al., 2012; Broughton et al., 2012).

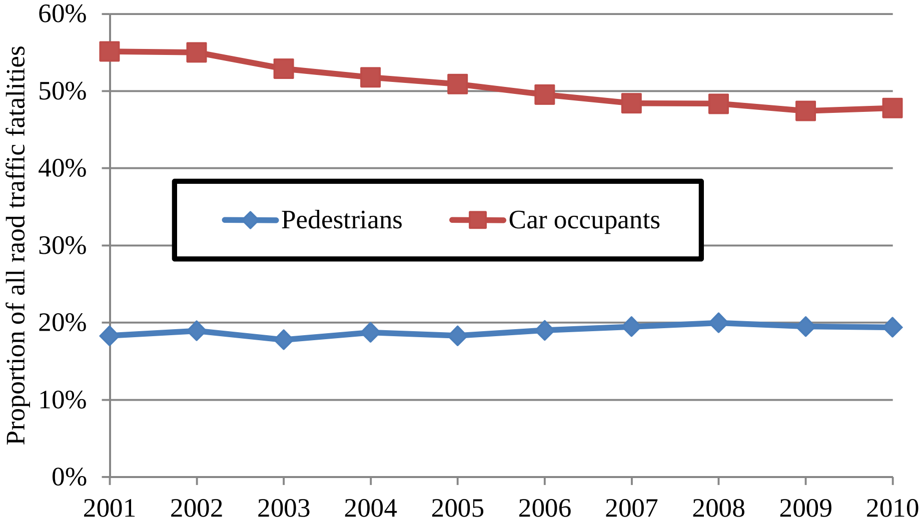


Fig. 10: Proportion of car occupants and pedestrian fatalities for all road transport fatalities in EU-19 from 2001 to 2010.

This thesis aims at reducing pedestrian causalities by enabling a better understanding of driver comfort zone boundaries for pedestrian encounters, and thereby potentially allowing a more efficient active safety system design and assessment (Papers II and III) as well as outlining the means to assess the integrated pedestrian protection offered by passenger cars which will allow the prioritizing of countermeasures and avoidance of suboptimization of passive or active systems that can occur when designing and assessing these systems in isolation (Paper I). Integrated assessment will enable the best overall solution for a given development effort, thus pedestrian protection proliferation will be faster with an integrated, compared to a separated, assessment.

Optimizing two sub-systems might not result in overall optimization. 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 not reflecting active safety performances on passive safety boundary conditions.

Key features of the outline for an integrated assessment (Paper I) are compared to other research proposals in Table 1. Some features of the proposed assessment are comparable with the Searson et al. method: Both methods reflect real-world impact speed distribution and evaluate injury reductions using injury probability modeled as a function of impact speed.

Contrary to previous research, it is necessary to consider all body regions of the pedestrian in the assessment, and to weight them according to real-world injury occurrence. Recalling Fig. 3, it appears that a majority of injuries are not addressed if considering head injuries only. This is difficult, because an impactor, for example, for pedestrian chest injuries is currently unavailable. Approximation methods, such as relating chest injury to HIC measured by the established head impactor (Han et al., 2012) might offer a solution.

The impact area and probability is suggested to be derived from real-world distributions. This could be done either from analysis of accident data, indicating where real-world impacts in the past took place (e.g. Fredriksson and Rosén, 2012; Kiuchi et al., 2014) or from simulations considering the body height of the pedestrian population (Mottola et al., 2013; Hamacher et al., 2013; Peng et al., 2011). Results from such a calculation should confirm which impact areas and point weighting are most appropriate.

Table 1: Key features of integrated assessment methods

Item	VERPS	Searson et al. method	PreEffect-iFGS	This thesis
Body regions considered	Head and lower leg	Head only	As Euro NCAP (head, upper and lower leg)	All
Weighting	No weighting, separate assessment	No weighting (head only)	Euro NCAP weighting (67%, 17%, 17%)	Real-world injury distribution
Injury risk reduction	Injury probability as function of impact speed	Injury probability as function of impact speed	Injury probability at MAIS level calculated with injury-shift method	Injury probability as function of impact speed
Collision speed	40 km/h	Real-world impact distribution	40 km/h	Real-world impact distribution
Measure for effectiveness	Risk reduction at chosen AIS level	General cost function, example of risk reduction at AIS3+ and AIS6 level	Risk reduction at chosen MAIS level	HARM (cost function)
Impact area and point distribution	Real-world: Vehicle specific by simulation	As Euro NCAP	As Euro NCAP	Real-world impact probability
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)	

Earliest activation timing for AEB or warning systems is suggested to be based on comfort zone boundaries in this thesis (Papers II and III). Seiniger et al. (2014) propose earliest activation time based on pedestrian deceleration capabilities and a lateral safety distance. Table 2 presents TTC values below in which system activation is either mandatory (no lateral safety distance) or possible (1m lateral safety distance) according to Seiniger et al. (2014). System activation above these values is unwanted. These values can be compared to comfort zone boundaries proposed in this thesis.

Using linear interpolation with TTC 2.6 s for 1 m/s pedestrian speed and TTC 2.2 s for 2m/s pedestrian speed, activation thresholds can be calculated (see Table 2). It must be noted that overlap, that is, the lateral position of the pedestrian with respect to the car front (for example 25% means that the pedestrian collided with 25% of the vehicle width measured from the side from which the pedestrian entered the driving corridor) has not been investigated in Papers II and III; thus it is assumed to have no influence on the desired system activation.

Table 2: System activation threshold TTC - activation below the threshold is wanted

	Seiniger et al. (2014)		This thesis
AsPeCSS scenario	System activation mandatory: Pedestrian unable to come to a complete stop	System activation possible: Pedestrian is able to stop at a safe distance from the driving corridor	System activation desired
V_{ped} = 3 km/h, overlap 50%	1.34	2.53	2.7
V_{ped} = 8 km/h, overlap 50%	0.82	1.27	2.1
V_{ped} = 5 km/h, overlap 25%	0.59	1.21	2.4
V_{ped} = 5 km/h, overlap 75%	1.31	2.03	2.4
V_{ped} = 5 km/h, overlap 50%	0.95	1.67	2.4

This thesis proposes earliest system activation thresholds that are earlier (larger TTC) than those proposed by Seiniger et al. (2014). Assuming that drivers appreciate system intervention when the comfort zone boundary is crossed and that brake onset is a good measure for comfort zone boundaries, the earlier activation time will not lead to dissatisfied drivers and system deactivation as indicated by Seininger et al. (2014), thus there will be no negative implication to pedestrian safety. On the contrary, earlier system activation allows more time to achieve greater speed reduction and will increase pedestrian protection offered by a system. The quantification of this additional protection offered needs to be quantified in future research. To do this, either the to-be-developed and outlined integrated assessment method, or computer simulation, can be used. For either method, the once crucial and not fully quantified factor is the reaction time of drivers when a collision warning is issued for an imminent pedestrian impact.

a) Influence of driving speed on TTC at brake onset

Brake onset TTC was independent of vehicle speed in the range of 25 to 55 km/h in this thesis. Fig. 11 depicts actual driving speed and TTC at brake onset for the experiments with 1 m/s pedestrian speed in the driving simulator study (Paper III) and the test track study (Paper II).

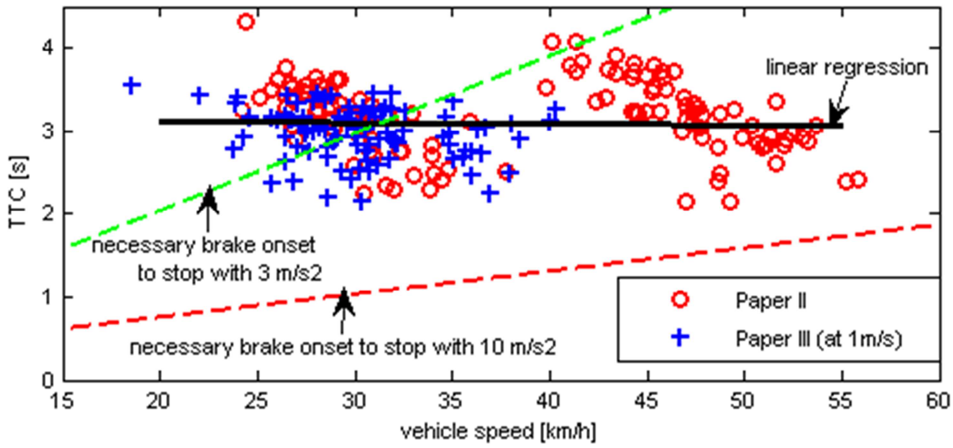


Fig. 11: TTC at brake onset and initial vehicle speed

A linear regression and the R^2 value indicate that no correlation between vehicle speed and TTC at brake onset exists. In the data from Paper II a negative trend of increased speed appears to exist when looking at each of the two target test speeds separately. This is likely to be linked to the test set-up where pedestrian starting time was controlled by the longitudinal distance: At speeds exceeding the target the TTC at visibility was below the targeted 4.0 s, resulting in turn to lower TTC values at brake onset. In the data for Paper III, where pedestrian starting was controlled by TTC and not longitudinal distance, no such effect was observable. This correlation within the two sets of Paper II seems to be a technical limitation of the test layout with no implications for the interpretation of results. Both studies (Papers II and III) were designed as an urban pedestrian crossing situation in the same layout. Thus, analysis of combined results of both test situations seems appropriate. It is however likely, that TTC at brake onset will not be constant in all situations.

Whether a vehicle can come to a full stop prior to a pedestrian entering the driving path depends on initial speed (v), brake onset (t), and brake deceleration (a). These parameters are interdependent through simple dynamics, and can be chosen from a wide range of driver collision avoidance strategies. Fig. 11 depicts necessary brake onset, given the vehicle speed, for two brake decelerations by the simplified vehicle dynamics model v=a(t-0.2). Obviously, drivers decelerating with 3 m/s^2 need to start braking earlier than drivers decelerating with 10 m/s^2, which is why the 3m/s^2 line is above the 10 m/s^2 line in Fig.11. Clearly, brake deceleration and brake onset time are, to some extent, substitutable. Further, drivers might adjust their initial speed to the environment. It is quite uncommon to drive at high speeds in areas where pedestrians might suddenly enter the road. The combination of environment and driving speed can cause discomfort leading to a reduction of the initial speed.

In this thesis, initial speed was externally controlled by instructing volunteers to drive at a specific speed, which was found to have no significant influence on brake onset. Brake onset had some influence on brake deceleration (Paper III). This implies that drivers seem to be somewhat more likely to adjust brake deceleration than brake onset for pedestrian encounters in urban environments. This, of course, has its limitations. At higher instructed initial speeds, drivers might reduce initial speed against instruction in case of restricted visibility, might choose to start braking much earlier in case of early visibility of the pedestrian, or might expect the pedestrian to take evasive action and not react at all, or attempt avoidance by steering.

For encounters with other vehicles, Gårder (1982) and Aoki et al. (2011) found TTC at brake onset to increase with driving speed. Driving speeds were higher in these studies, making it more difficult to come to a full stop by adjusting brake deceleration alone, thus making the finding of a dependency between driving speed and TTC at brake onset more likely.

b) Activation time of active safety systems

Ljung Aust and Domboovskis (2013) define the driver's comfort zone boundary as the separation between desired and undesired false positive activation for warnings, and discuss it for False Positive activations of lane departure warnings. This definition balances driver acceptance and system performance: Activation is early enough for high performance but not so early as to cause driver annoyance and mistrust in the system. Mistrust in the system can lead to a deteriorated performance of warning systems (Bliss and Acton, 2003; Abe and Richardson, 2006).

For warning systems, there is a necessity to warn before the safety zone boundary to regain control: A warning at the edge of losing control will, given that a human driver always requires some time to react to a warning, never be able to regain control. Most active safety warning systems are designed with the aim of avoiding collisions, not only mitigating them. Thus, warning before the safety zone boundary is essential.

For automatic braking, there is generally no relation between driver trust and system performance. One exception would be that 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 passing the safety zone boundary 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 zone, automatic braking would be considered a nuisance in the same way a warning would. Thus, automatic braking should not occur before passing the comfort zone boundary, in the same way that a warning should not occur. While warnings should take place at the comfort boundary zone for system performance reasons, automatic braking could take place somewhere between the comfort zone boundary and the safety zone 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.

Driver personality and ability, as well as road and vehicle conditions and the traffic situation under consideration, are likely to be influential. Thus, the comfort zone boundary is likely to differ among individuals. The selection of appropriate percentile values of a population may be suitable for determining current system design and assessment. Driver adaptive solutions may be applied in the future.

In conclusion, both warnings and automatic braking should not be activated prior to the comfort zone boundary. Thus, the definition of comfort zone boundaries from empirical data is highly relevant for the assessment of active safety systems that either warn the driver or brake automatically. Knowing 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, assessments could penalize activation occurring before this threshold has been reached. Using such a False Positive test contributes to the achievement of the highest overall safety performance by allowing True Positive performance increase due to earlier activation only within reasonable boundaries not having detrimental effects on safety via driver mistrust.

c) Metrics for the assessment of benefit

Pedestrian protection assessments of vehicles ultimately lead to a rating. Regulatory bodies use a pass/fail rating deciding whether a vehicle can be placed on the market. Euro NCAP uses a 5-step rating scale for pedestrian protection as part of the overall assessment aiming at enhancing availability of independent information on the safety level and promoting the use of safer cars throughout Europe.

Scores are based on acceptance levels of injury criteria measurements related to injury probability, which are then aggregated to an index. Acceptance levels are derived from injury risk curves established for the criteria considered in the rating. In general, lower probability of injury for a pre-defined injury severity level will result in higher scores. However, the injury severity levels considered and acceptable levels of injury risk vary for different body regions and measurements. Scores from different body regions are aggregated to cover the entire vehicle. In JNCAP scores are weighted according to AIS3+ accident frequency of the particular combination of body region and vehicle part under assessment.

Evidently, implicit trade-offs between different scores exist. For example, reducing AIS3+ injury risk for the lower leg from 25% to 10% for 1/3 of the lower leg test area could have the same effect on the rating as reducing AIS3+ head injury risk from 35% to 30% for 1/6 of the test area. The predominant use of specific injury severity might not reflect improvements made at a higher or lower severity level potentially having an effect on the overall benefits of pedestrian protection. For example, a design resulting in a 30% risk of fatal head injuries might be awarded the same zero score as a design resulting in a 70% risk when both have a 100% risk of injury at the specific injury level under consideration.

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. Further, multiple targets and measures could be defined, e.g. separate reduction targets for fatalities and severe injuries.

Indicators for the benefit offered for pedestrian protection could also be aggregate measures, for instance using the Injury Severity Scale (ISS), medical impairment, Quality of Life Year losses, 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). Cost values for European pedestrian injuries might differ because medical treatment and injury types may differ. My calculations using GDIAS 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.

The Risk of permanent medical impairment (Rpmi) is another aggregate measure 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 medical 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). As with HARM, it is questionable for Rpmi as well whether values are directly applicable. 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 different Rpmis when averaging for a specific body region and severity level. The influence of a different injury spectrum was confirmed using STRADA data (16989 injuries for occupants and 8725 injuries for pedestrians). For each injury sustained by a car occupant or pedestrian, the Rpmi at the 10% level was calculated using the tabulated values established by Malm et al. (2008). Thus, these calculations did not validate if the Rpmi level sustained for the same injury differed between car occupant and pedestrians, but verified if different injury types lead to different RPMIs. 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%. Differences are presented in Table 3. Overall, the application of the Rpmi metric, developed for car occupants, to pedestrian injuries appears reasonably accurate. There was no strong evidence against doing so.

Table 3: Percentage differences of pedestrian 10% Rpmi (my calculation) minus occupant 10% Rpmi (Malm et al., AAAM 2008). Blank cells: No data available for pedestrians. Positive numbers indicate higher risk for pedestrians

Body region / AIS	1	2	3	4	5
Skull/Brain	0.3	-0.8	8.5	5.0	0.0
Cervical Spine	-0.5	3.2			
Neck	0.0				
Face	-0.4	-6.0	-10.0		
Arm	0.0	-0.1			
Leg	0.0	0.2	-1.0		
Chest	0.0	0.0	0.0	85.0	
Thoracic Spine		0.1			
Abdomen		0.0		-5.0	
External	0.0				

Limitations of this thesis

The proposed methodology is in its infancy, and a substantial amount of further work is needed to establish assessment protocols. The methodology is limited in its application to active safety systems operating automatically or warning the driver, aimed at an immediate reaction, and to those systems that aim at reducing impact speed. Thus, the benefit of other systems, such as driver support or steer avoidance, cannot be assessed, while it is likely that they have at least some benefit.

The methodology relies on the testing of active safety systems in representative scenarios, and 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 methodology. Hardware tests are preferred for the integrated methodology due to their widespread use in assessment, and difficulties in establishing model validity in virtual testing. 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 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 methodology proposed relying on separated hardware testing for integrated assessment.

Comfort zone boundaries were measured and quantified experimentally. The experiments were on a test track using a driving simulator. It is always questionable whether such “laboratory experiments” accurately represent “real-life” situations and are applicable outside the laboratory. While efforts were undertaken to replicate “real-life” situations, and similar results were obtained independently in a track study and a driving simulator. These results are encouraging, but are nevertheless, results of laboratory experiments. Repeatability and control weighed in heavily for this thesis. Naturalistic Driving Studies, with their strong face validity, were not conducted, since the time and money needed to collect a similar amount of data would have far exceeded that which was available.

The influence of two driving and pedestrian speeds on comfort zone boundaries were quantified. 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 that come to mind. Rightfully, one might argue that the work presented misses potentially influencing factors, and does not quantify comfort zone boundaries completely.

6) Conclusions

A concept for the development of an integrated pedestrian safety assessment methodology is presented in Paper I. Further work is needed to collect or create sufficient data to obtain a usable and accurate assessment method from this concept.

Comfort zone boundaries for pedestrian crossing situations were quantified. TTC was identified as the most suitable measure for comfort zone boundaries. Comfort zone boundary TTC was independent of car travelling speed but dependent on pedestrian crossing speed. The 90 percentile value for TTC at the comfort zone boundary for 1 m/s pedestrian speed was 2.5 s in Paper II and 2.6 s in Paper III. The value for pedestrian speed of 2 m/s was 2.2 s TTC identified in Paper III.

These values can be used to differentiate between *desired* and *undesired* False Positive system activation, which in turn can help in designing False Positive test procedures to provide guidance on balancing between True Positive system performance and False Positive driver annoyance in an integrated pedestrian safety assessment methodology.

7) Future work

Influencing factors for comfort zone 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 should be studied. This could provide guidance for deciding on the earliest desired active safety system intervention.

Further work is required to predict and assess the effect that such an active safety system intervention will deliver. The outline for an assessment that will predict the integrated benefit of passive and active safety performance was presented in this thesis. To reach an operational method, further substantial research is needed on:

- Injury risk curves and aggregate benefit measures
- Impactor response prediction for various impact speeds
- Impact probabilities for different vehicle areas, at different speeds
- Reactions of drivers to warnings for pedestrians
- Validation or calibration procedure of the assessment method against accident data

The effect of different system activation thresholds for warnings needs to be quantified to motivate further research in this area. The operational method for integrated pedestrian safety assessment may provide the means. A crucial part is driver reaction times to a warning that must be established for a variety of situations.

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