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

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Abstract Automated Emergency Braking systems reduce impact speeds, and consequently, injuries in car-to-pedestrian impacts. The development of assessment methods for these systems has received considerable attention. Forward Collision Warning systems similarly aim at reducing impact speed, but have received less attention. Casualty cost reductions of several simplified but realistic Forward Collision Warning and Automated Emergency Braking systems were calculated using simulations and a modified AsPeCSS method. Automated Emergency Braking systems were assessed to result in approximately 25% casualty cost reductions. Forward Collision Warning effectiveness ranged from "no benefit" for an audio-visual warning system with late activation, to a benefit of 25 % casualty cost reduction for an early activating warning system including an additional short brake pulse. As Forward Collision Warning seems to have the potential to reduce pedestrian casualties of the same magnitude as Automated Emergency Braking, the authors suggest including a Forward Collision Warning assessment in a modified AsPeCSS method to rate pedestrian protection of cars.

Keywords AEB, assessment, benefit, FCW, pedestrian

I. INTRODUCTION

Injury severity in car to pedestrian impacts is strongly dependent on impact speed [1-4]. Active safety systems aimed at reducing impact speed by warning the driver of an imminent impact, and automatic brake application, are currently available on the market. Ideally, such systems reduce impact speed to zero, avoiding impact and injury altogether. But even if impacts still occur impact speed can be reduced, with a following reduced risk of injury and injury severity [2-3]. Reducing impact speeds through active safety systems might allow an optimized passive safety design for lower impact speeds resulting in improved overall pedestrian protection when active safety systems activate. As the systems currently do not activate in all impact conditions, such re-design of passive safety for lower impact speeds might currently trade-off improved safety for most pedestrians and worsened protection for some pedestrians still experiencing high speed impacts. The full potential for improved overall protection will only be available when active safety systems reliably activate in all impact conditions.

Automated Emergency Braking (AEB) systems have a great potential for pedestrian injury reduction [5-12]. Much less attention has been directed to pedestrian Forward Collision Warning (FCW) systems, which have been assumed to have little effect [6].

Not surprisingly, most current assessment methods for active safety pedestrian protection measure only the AEB system's impact speed reduction in defined test scenarios, and score these reductions against desired values of speed reduction [13-15]. Hardware tests on test tracks are commonly used, i.e. a vehicle controlled by a driving robot and equipped with an active safety system to be assessed for its achieved speed reduction approaches a dummy representing a pedestrian [16]. A protocol to assess FCW systems was developed only by the consortium "advanced Forward-looking Safety Systems" (vFSS) [17]. In this protocol a driving robot applies the brakes 1s after the warning is issued as an alternative to speed reduction by automated brake activation.

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An integrated pedestrian safety assessment method, combining active and passive safety, and modelling their interactions, has recently been proposed by the EU FP7 project “Assessment methodologies for forward looking integrated Pedestrian, and further extension to Cyclists Safety Systems” (AsPeCSS) [18]. The AsPeCSS method estimates and integrates the benefit of improved front end structures for passive safety and AEB for active safety, in terms of casualty costs. Contrary to the quantification of benefit in terms of speed reduction for purely active safety assessments, the AsPeCSS method allows a direct comparison of passive and active safety measures. Edwards et al. [18] used this method to compare the benefit of AEB and A-pillar airbags. However, the AsPeCSS method does not have the capability to assess the benefits of FCW systems.

This paper quantifies expected benefits (in terms of casualty costs) of both FCW and AEB systems using a modified AsPeCSS method, and thereby suggests a design for FCW assessment.

II. METHODS

AsPeCSS assessment method

The AsPeCSS integrated pedestrian safety assessment method [18] was used to quantify the benefit of AEB and FCW systems in terms of casualty cost reduction for a generic vehicle with an assumed good Euro NCAP passive safety score (‘hybrid car with good Euro NCAP passive safety rating’ described in [18]). AsPeCSS developed two versions of the assessment method. While following the same logic, one version was tailored to GB accident data and another one to German accident data. The German version is recommended as default choice [18] and used in this study. For active safety system testing the AsPeCSS method prescribes five test scenarios of pedestrian dummies crossing the road in front of a vehicle, which are weighted with their relevance for fatally and severely injured pedestrian in Europe (Table I). In these scenarios speed reduction of an AEB system is measured for a set of test driving speeds. The active safety system test results are then weighted and used to modify the distribution of impact speeds at which pedestrian impacts are expected to occur with the vehicle under assessment. Passive safety protection is estimated for all speeds of the modified impact speed distribution. The measured responses of pedestrian sub-system impactors are converted into injury risk and finally casualty cost. Casualty costs were taken from an economic assessment detailed for AIS level and body region in the USA including medical expenses, wage loss, and loss of quality of live. These costs were summed for the 5 impact scenarios, all impact speeds and areas of impact to give the total casualty cost. This cost is calibrated to match an independent benefit estimate and subtracted from a reference car to give cost reduction or total expected benefit.

As the protection level increases with reduced impact speed, higher speed reductions will provide greater benefit in terms of casualty cost within the limits of the test speeds. The AsPeCSS method tests at speed ranges of 10-50 or 20-60 km/h, see Table I. Impacts are assumed to be avoided if impacts are avoided at the lowest test speed, and above the test speed range it is assumed that no speed reduction can be achieved. The test scenarios described in [19] are summarized in Table I.

TABLE I
ASPECSS TEST SCENARIO DESCRIPTION

	Walking (slow) adult	Running adult	Walking adult	Walking adult	Walking child obstructed
Scenario number	1	2	3	4	5
Weight	12.5%	3.4%	9.8%	4.9%	0.9%
Pedestrian speed	3 km/h	8 km/h	5 km/h	5 km/h	5 km/h
Dummy type	Adult	Adult	Adult	Adult	Child
Dummy initial position	Farside	Farside	Nearside	Nearside	Nearside
Vehicle test speeds	20-60 km/h	20-60 km/h	10-50 km/h	10-50 km/h	20-60 km/h
Obscuration	No	No	No	No	Yes
Impact point	50% (Center)	50% (Center)	25% (Nearside)	75% (Farside)	50% (Center)

Driver model

Brake reaction times and brake force response of mildly distracted drivers to FCW systems were studied within the AsPeCSS project [20]. However, the assessment method considers only AEB systems in testing [19]. In the AEB assessment, speed reduction is measured by the vehicle's automated brake response. For FCW assessment, brake response of the driver to an FCW needs to be modelled to measure speed reduction of the vehicle. This paper suggests adding a driver model based on a recent Driving Simulator study [21]. In this study volunteers approximately representative for the population of Japanese driving licence holders with respect to age (mean 48 years, standard deviation 17 years) and gender (55% male) were subjected to a single FCW event while driving in a simulated urban area at a self-regulated speed of 30 km/h. An adult pedestrian was crossing the road from the near side at 90 degree and 1 m/s walking speed in a collision course with the front centre of the vehicle. Driver gaze was diverted to a passenger-seat mounted screen inside the vehicle where volunteers had to memorise a displayed number sequence. Brake response was quantified for an audio-visual FCW system and an audio-visual FCW system with an added triangular brake pulse of 0.2 s duration and 3 m/s^2 maximum deceleration, both activated at 1.8s Time To Collision (TTC). Reaction rates (proportion of the 13 volunteers per Human Machine Interface (HMI) that applied the brakes prior to the simulated pedestrian impact), mean brake response time (time from warning to brake pedal force >10 N for those volunteers applying brakes), mean brake jerk and mean maximum deceleration are summarized in Table II.

TABLE II

DRIVER MODEL PARAMETERS

HMI type	Reaction rate	Brake reaction time	Brake jerk	Max. deceleration
Audio-visual only	62%	1.0 s	10.7 m/s^3	6.8 m/s^2
Added brake pulse	100%	0.8 s	10.7 m/s^3	6.8 m/s^2

AEB and FCW model

The performance of the AEB and FCW were assumed to activate at two different timings: Firstly, late activation when a pedestrian can no longer avoid entering the driving corridor of a vehicle ('green zone' in [19]) and secondly, early activation at the time of crossing comfort zone boundaries [22-23]. Comfort zone boundaries indicate the transition point from normal situations to uncomfortable driving situations in which the driver will take corrective action and can be quantified, among other measures, in terms of TTC. Using linear interpolation with a TTC of 2.6 s for 1 m/s pedestrian speed and a TTC 2.2 s for 2 m/s pedestrian speed [23], activation thresholds were calculated in Table III. It must be noted that the influence of overlap, or impact point, has not been investigated. Thus, it is assumed to have no influence on the desired system activation.

TABLE III

SYSTEM ACTIVATION TIMING FOR ASPECSS TEST SCENARIOS

Scenario	Late activation: Pedestrian unable to stop	Early activation: Comfort zone boundary
1: V_{ped} = 3 km/h, overlap 50%	TTC 1.34 s	TTC 2.7 s
2: V_{ped} = 8 km/h, overlap 50%	TTC 0.82 s	TTC 2.1 s
3: V_{ped} = 5 km/h, overlap 25%	TTC 0.59 s	TTC 2.4 s
4: V_{ped} = 5 km/h, overlap 75%	TTC 1.31 s	TTC 2.4 s
5: V_{ped} = 5 km/h, overlap 50%	TTC 0.95 s	TTC 2.4 s

The systems were assumed to be ideal, thus able to be activated at the desired time for all unobstructed test scenarios. In these unobstructed test scenarios the pedestrian was assumed to be visible to the system long enough to allow activation at these times. For the obstructed test scenario with visibility at a TTC of approximately 1.37 s, FCW and AEB were likewise assumed to activate after approximately 0.4 s for detection and classification at a TTC of 0.95 s.

The “early” and “late” FCW systems were each modelled with two different HMIs: An audio-visual warning only (AV) and an audio-visual warning with added brake pulse (BP). This led to a total of six investigated systems; AEB early, AEB late, FCW audio-visual early, FCW brake pulse early, FCW audio-visual late, and FCW brake pulse late.

The brake responses for FCW systems were modelled with a reaction rate and brake reaction time specific to the HMI under consideration, and a jerk of 10.7 m/s^3 and maximum deceleration of 6.8 m/s^2 valid for all types of HMI (Table II). The AEB systems were modelled to always activate as intended (100% reaction rate) with no delay, a jerk of 30 m/s^3 and a maximum deceleration of 10 m/s^2.

Table IV summarises TTC at brake activation either automatically by driver input per assessment scenario for the six systems. One should keep in mind that audio-visual FCW have a reaction rate of 68%, this system performance is modelled using 68% of the accident population with brake activation times as given in Table IV, and 32% of no brake activation at all. Further AEB and FCW systems differ not only in brake activation time but also brake application.

TABLE IV
START OF BRAKING TTC FOR AEB AND FCW SYSTEMS IN THE ASSESSMENT SCENARIOS

Scenario	AEB		Forward Collision Warning			
	Late	Early	Late		Early	
			BP	AV	BP	AV
1	1.34	2.7	0.54	0.34	1.9	1.7
2	0.82	2.1	0.02	-	1.3	1.1
3	0.59	2.4	-	-	1.6	1.4
4	1.31	2.4	0.51	0.31	1.6	1.4
5	0.95	0.95	0.15	-	0.15	-

III. RESULTS

For each of the six systems and the five test scenarios, speed reductions were calculated for an assumed driving speed of up to 140 km/h as presented in the Appendix. Fig. 1 shows the maximum avoidance speed, that is, the maximum speed at which the vehicle can still come to a complete stop prior to the pedestrian impact position, and avoid an impact altogether. For audio-visual FCW systems the maximum speed reduction for the proportion of drivers reacting to the warning is depicted, the maximum speed reduction of drivers not reacting at all is, obviously, zero. As expected, the early AEB system had the highest avoidance speed in all test scenarios, exceeding the maximum test speed largely in scenarios 1 to 4. In terms of maximum speed reduction, the early AEB was clearly the single most performant system. Late AEB and both early FCW systems had a somewhat comparable maximum speed reduction performance. AEB and early FCW systems’ maximum speed reduction exceeded maximum test speed in scenarios 1 and 4, which means that when using the AsPeCSS method no performance difference (no tests at higher speeds) and no benefit difference (no benefit assumed above test speeds) is noticeable for these scenarios. In scenario 3 the early FCW systems achieved higher speed reduction than the late AEB system. In scenario 5, for all FCW systems driver reaction time exceeded assumed activation time, leading to no speed reduction. Both late FCW systems showed low maximum avoidance speed (scenario 1 and 4) or no avoidance at all (scenarios 2, 3, and 5).

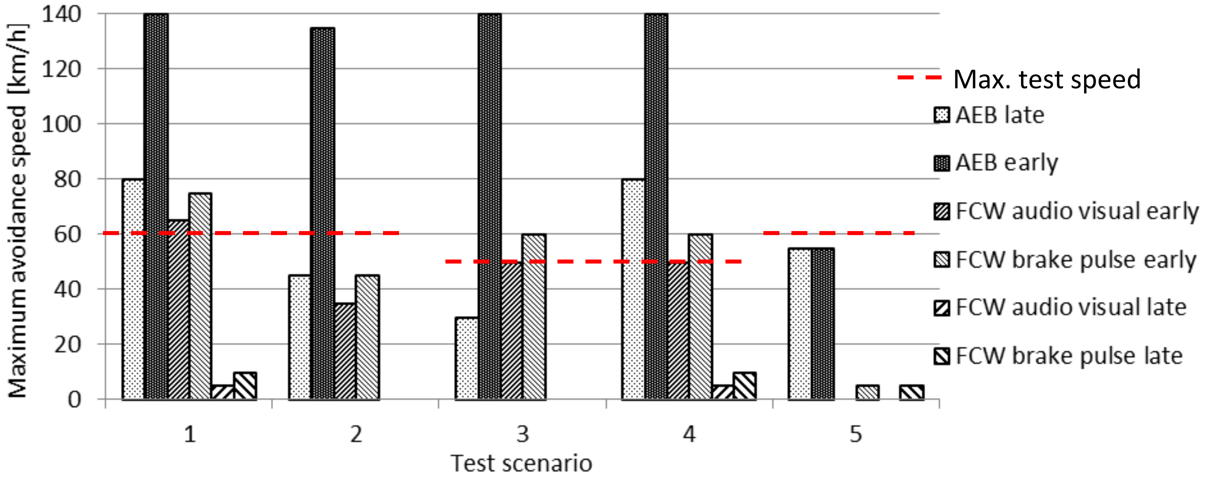

Fig. 1. Maximum avoidance speed of AEB and FCW systems by test scenario (bars) and maximum vehicle test speed (dashed lines)

The AsPeCSS method was used to calculate casualty costs for the respective speed reductions of the six systems. Costs normalized with no system are presented in Fig. 2; the lower the cost, the higher the benefit. Late FCW systems gave almost no benefit (audio-visual), or as little as a 5% reduction of casualty costs. The early FCW system with a brake pulse was assessed to give a higher reduction of 25%, which was as much as the late AEB system, and nearly as much as the early AEB system with 26%. These results show that one FCW system design was as effective as AEB systems for pedestrian protection, notwithstanding that another design was giving (with 0.1% calculated reduction) no benefit.

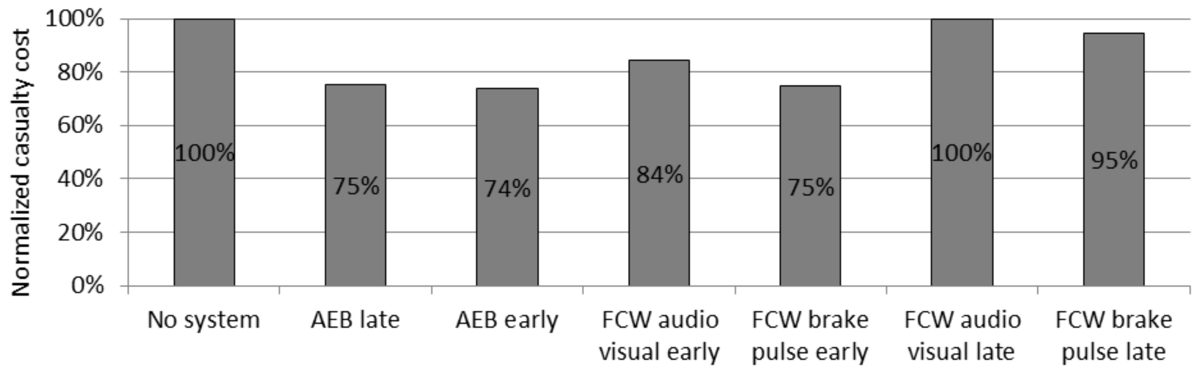

Fig. 2. Normalized casualty costs of AEB and FCW systems

Sensitivity

The benefit of an early brake pulse FCW in Fig. 2 was calculated for activation at comfort zone boundaries and mean driver response [21]. To assess sensitivity, benefits for the 10 percentile least performant driver response (1.0 s reaction time, 5.3 m/s^3 jerk, 3.6 m/s^2 max. deceleration), and 90 percentile driver response (0.6 s reaction time, 17.3 m/s^3 jerk, 10.8 m/s^2 max. deceleration) according to [21], were calculated with a variation of activation time of +/- 0.5 s as presented in Table V.

One can see that for the mean driver response a variation of activation timing affected the casualty cost estimate by less than 1%, however, even later activation lead to a sharper decrease of benefit (not depicted). For the 90 percentile driver response, all impacts in scenarios 1-4 were avoided, except scenario 2 at 60 km/h. Thus, there was no noticeable influence of activation timing on the benefit estimate. Only the 10 percentile driver response revealed strong dependency on activation time, which was expected since at lower deceleration levels speed reduction is more dependent on activation time. Overall, the estimated casualty costs for early brake pulse FCW (75%) appear resistant to smaller variations in activation time and driver response, see Table V.

TABLE V
SENSITIVITY OF CASUALTY COST TO VARIATION IN DRIVER RESPONSE AND ACTIVATION TIMING

Activation time	10 percentile 1.0 s, 5.3 m/s^3, 3.6 m/s^2	Mean 0.8 s, 10.7 m/s^3, 6.8 m/s^2	90 percentile 0.6 s, 17.3 m/s^3, 10.8 m/s^2
Comfort zone boundary -0.5 s	89%	76%	75%
Comfort zone boundary	79%	75%	75%
Comfort zone boundary +0.5 s	75%	75%	75%

IV. DISCUSSION

Driver model

In light of the strong potential of FCW systems found in this study, achieving a casualty cost reduction comparable to AEB systems using a modified AsPeCSS method, it seems necessary to include FCW performance tests in the assessment of pedestrian protection. Implementation can be straightforward, as has been demonstrated in this paper. Speed reductions for the test scenarios of the assessment method under consideration have to be measured for FCW systems, which in turn requires modelling of driver reactions to a warning. Such reaction models could use mean values reported from the experiment by [21] assuming heavily distracted drivers, i.e. drivers with gaze diverted from the road and high mental load. No pre-crash brake assist boosting maximum deceleration levels was assumed, but could be implemented. This is a more conservative approach than modelling driver reaction reported for mildly distracted drivers (following instructions of a navigation system with gaze not diverted from the road) where all volunteers were reported to brake prior to impact, and had a slightly shorter reaction time of 0.7 s for an audio-visual warning at a TTC of 1.8 s [20]. Driver distraction is a major contributing factor to pedestrian accidents [24-25] with “missed observation”, that is the pedestrian not being in the momentary field of view of the driver, being the dominant distraction [24]. Thus, modelling heavily distracted drivers with gaze diverted from the road was regarded appropriate. Obviously, driver reaction times for both heavily and mildly distracted drivers could be modelled for the assessment of pedestrian FCW systems.

Reported deceleration levels [21] allow more direct calculations of speed reduction with simplified models for AEB and FCW. The modelled brake force levels in [20] first require developing another model relating brake pedal force to vehicle deceleration. It is, however, unclear which property remains constant when drivers change vehicles, deceleration levels or brake force levels (or none of them) as “the speed and force with which a typical driver presses the pedal in an emergency is partly dependent on the characteristics and feel of the brake pedal” [26]. The decision for how driver reaction is to be modelled should be ultimately based on the chosen property’s resistance to changed vehicles, or the ability to account for the influence of brake pedal characteristics on the chosen property.

Driver reactions were assumed independent of FCW activation timing. Values reported for activation at a TTC of 1.8 s [21] were used for activation in a range of 0.6-2.7 s in this paper. While this is somewhat plausible for distracted drivers in the applied range where the pedestrian will in any case represent an immediate threat after redirecting the gaze direction to forward roadway, it was reported for mildly distracted drivers that brake reaction time increases with brake activation time before collision, which means that the reaction is faster with increased urgency [20]. Further studies should quantify the influence of variations of FCW activation time on the brake reaction of heavily distracted drivers.

To create a test procedure for pedestrian FCW the available AEB procedures would need to be re-designed in a way that a driving robot applies the brakes of the vehicle in accordance with the driver model. This has been previously done for car to car impact assessment [13][27] and pedestrian assessment [17] and is thus expected to be readily implementable.

One should keep in mind that the driver model suggested in this paper is valid only for the HMI for it was designed, that is firstly a audio-visual warning and secondly a system with an added brake pulse. Thus, assessing another system would require in a strict sense to create a driver model for exactly the system under assessment. Further research might enable prediction of driver reactions based on system design and scenario characteristics, and allow a clear statement under which circumstances and to which limit driver models are generalizable. The natural variation of driver reactions will lead to variations in FCW effectiveness estimation as shown in Table V. Thus, uncertainty for “fleet average” FCW effectiveness estimates will be higher compared to AEB effectiveness estimates.

Comfort boundaries for the FCW model

This paper quantified the benefit to two different activation times of AEB and FCW systems, which are not the only possible activation times. The selection was made to represent a somewhat typical late activation, which is thought to reduce false positive activation [28], that is, reducing system activation where the traffic situations even without system activation would not have led to an impact. Such considerations are important as driver dissatisfaction with the systems might lead to their deactivation or deteriorated response to warnings [29-30].

However, not all false positive activations necessarily lead to driver dissatisfaction, some understandable false positive activation might even be necessary to enable drivers to be aware of the functionality of the systems [31]. This led to the definition of early system activation at driver comfort zone boundaries. Acceptance of system activation can be measured by its relation to brake activation timing of the driver during attentive driving [22-23]. Driver initiation of braking in attentive driving indicated discomfort with the situation and a (potential) hazard. Thus, if distracted for some reason and initially misjudging the situation, when being focused on the situation after system activation, drivers will see the situation as potentially hazardous and appreciate activation. Thus, driver comfort zone boundaries measured in experiments with attentive drivers [22-23] are suitable to determine system activation time for distracted drivers who following system activation become attentive. It might however be the case that, being aware of their distraction, drivers would appreciate an even earlier warning as raising attention levels, orientation, and other necessary additional activities for the distracted driver take time. To verify this hypothesis a different type of analysis is needed: Subjective driver response on the desirability of issued warnings for various activation times needs to be collected. This will necessarily raise issues to objectify subjective responses and to find suitable repeated-test designs.

Furthermore, driver comfort zone boundaries were taken as percentile values of the study’s population of drivers. Given various driving styles and preferences for brake activation more accurate comfort boundaries of an individual driver might require driver adaptive systems. Drivers might choose a pre-defined setting from a simple switch. Comfort zone boundaries might be estimated, before driving, by age and gender of the driver, which were shown to influence brake activation time [32]. Alternatively, they might be estimated while driving from exhibited braking behaviour [33].

AsPeCSS method

This paper suggests use of a modified AsPeCSS method to quantify benefits in terms of casualty cost reduction for any combination of front end structure design for passive safety protection and speed reduction systems (AEB and FCW) for active safety protection. Only one configuration of passive safety with a good European New Car Assessment Programme (Euro NCAP) passive safety score is considered to illustrate the implementation of FCW and compare it to AEB. The full potential of the AsPeCSS method to compare different types of active and passive safety configurations for a specific vehicle is not made use of in order to keep this paper short and focused. For the estimation of “fleet average” benefits of AEB and FCW other methods could also be applied. For example, [34] used “fleet average” injury risk curves making the passive safety assessment obsolete. However, the aim of this paper is to illustrate FCW assessment for one passive safety configuration, and make such assessment available for any vehicle specific configuration of AEB, FCW, and passive safety. For such a vehicle specific assessment, one must be aware of the limitations of the AsPeCSS method.

Chest injuries are frequently observed in accident data [35-36], but not specifically tested. They are assumed to linearly relate to the specifically tested head, upper leg and lower leg protection [18]. The biofidelity of the impactors for the performed tests can be questioned.

The AsPeCSS method, and therefore this paper, uses the Upper Leg test procedure developed by the European Enhanced Vehicle-Safety Committee Working Group 17 (EEVC WG 17) [37] as it was used in Euro NCAP until 2014, to assess pelvis and femur injury risk. From 2015, a revised test procedure is used by Euro NCAP [38]. Injury assessment thresholds for force remained at 5-6 kN, but moment thresholds were changed from 300-380 Nm to 285-350 Nm [39]. Biomechanical reference and related injury risk curves are not publicly available. Considering the limited changes of the new procedure, the inaccuracy of continued use of the EECV WG17 injury risk curves with the 2015 Euro NCAP test procedure are probably small. Once injury risk curves for the new procedure are established, it would be straightforward to implement them in a revised AsPeCSS version.

The relationship between impact speed and impactor response for injury criteria of the head, upper leg and lower leg are approximations for a limited range of test speeds based on CAE (Computer Aided Engineering) simulation [40]. The relation between impact speed and the Head Injury Criterion (HIC) initially proposed for bonnet impacts without bottoming out [41], that is without bonnet deformations so large that underlying hard structures are hit, were confirmed by the CAE simulation. Should bottoming out occur, this relation is no longer valid, and either modelling of bottoming out [42] or tests at more than one speed might be required. As is so often the case, test efforts and accuracy are a trade-off.

Also, the relation between impact speed, pedestrian height and head Wrap Around Distance (WAD) is based on CAE simulations of a limited number of vehicles, impact speeds and pedestrian sizes, and is an approximation [43]. This approximation, as the speed impactor response relation, is based on current vehicle designs. Should vehicle designs in the future have much stiffer or softer front ends or very different shapes, these relations may no longer be accurate.

Assessment of systems that deploy and alter head impact WAD is not foreseen in the AsPeCSS method but could be implemented given sufficient evidence to quantify such influence. Further, only a subset of possible active safety systems can be assessed. Systems not aiming at immediate impact speed reduction, but at earlier driver assistance and behaviour alteration, such as fatigue monitoring or improved illumination, cannot be assessed. Also, systems not aiming at speed reduction, but at steer avoidance, cannot be assessed.

The AsPeCSS method tests at speed ranges of 10-50 or 20-60 km/h and above test speed range it is assumed that no speed reduction can be achieved. The restriction is mainly motivated to keep test efforts within reasonable limits, and to test only the speeds at which the vast majority of impacts occur. Such a restriction need not be applied for the theoretical model to calculate speed reductions in this paper. AEB effectiveness in reducing pedestrian was shown to substantially increase (from 29% to 48% for fatalities and from 35% to 42% for severe injuries) when the systems operate also above 60 km/h [10]. To confirm such effect with the AsPeCSS method no limitation of test speeds was assumed, even though this might pose difficulties in application as brake initiation will take place up to more than 100 m before impact. Calculating speed reductions for the theoretical system of up to 140 km/h, does indicate that some additional benefit can be obtained when such systems operate at speeds higher than 50 or 60 km/h. The early AEB system's avoidance speed exceeds test speeds by the greatest margins (Fig.1), indicating its efficient operation at the highest speeds. Consequently, it gains the greatest additional benefit reducing casualty cost by a further 5% to 69% (Table VI). Likewise, the influence on the other systems remains limited by an additional 0-4%. These effects are lower than in a previous study [10], attributable to different scenario weights and targeted injury levels. Detailed speed reductions for each of the six systems and five scenarios are presented in the appendix.

TABLE VI
CASUALTY COST FOR SYSTEMS OPERATING UP TO MAXIMUM TEST SPEED AND UP TO 140 KM/H

Normalized casualty cost	AEB late	AEB early	FCW audio-visual late	FCW audio-visual early	FCW brake pulse late	FCW brake pulse early
No benefit above test speed	75%	74%	100%	84%	95%	75%
Benefit up to 140 km/h	72%	69%	100%	82%	95%	71%

Given these limitations, it is clear that the AsPeCSS method will provide an approximate estimate of pedestrian protection offered by vehicles. However, this is true for almost any assessment method, and is somewhat mitigated by the aim to calculate relative performances in a rating where approximations are at least identical for the vehicles being assessed. Thus, the absolute effect of FCW systems on pedestrian injury outcome calculated with a modified AsPeCSS method should be verified using other methods, for example simulation of FCW systems in traffic or single accident reconstructions as reported for AEB systems [10][44].

V. CONCLUSIONS

If a well-designed warning is used, FCW can be as effective as AEB to reduce casualty costs of pedestrians impacted by vehicle fronts. A modified AsPeCSS method was used to estimate a casualty cost reduction of 25% for a FCW system with an audio-visual and brake pulse warning, which is similar to the estimated reductions for AEB of 25 to 26 %. The effectiveness of FCW systems was found to be reduced, however, with later activation and other HMIs.

In light of this significant potential of FCW, the authors suggest including an FCW assessment for the quantification of overall safety benefit in the AsPeCSS method using a driving robot acting in response to an FCW. This response could be modelled from a recent study on heavily distracted drivers [21] as done in this paper.

VI. ACKNOWLEDGEMENT

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VIII. APPENDIX

The number of impacts per 5 km/h category of impact speeds for no system as baseline and AEB and FCW systems as calculated with the AsPeCSS method [18] are presented in Table A-I. Whereby none of the systems are assumed to reduce impact speeds above scenario test speeds, there are no differences in the number of impacts with impact speeds above 60 km/h (the maximum test speed). The early activated AEB system has the highest number of avoided impacts (6678 cases of zero impact speed).

TABLE A-I
NUMBER OF IMPACTS PER 5 KM/H CATEGORY OF IMPACT SPEEDS ASSUMING NO BENEFIT ABOVE MAXIMUM TEST SPEED

Impact Speed [km/h]	No system	AEB late	AEB early	FCW audio-visual late	FCW audio-visual early	FCW brake pulse late	FCW brake pulse early
0	0	6121	6715	244	3957	868	6497
0-5	2270	1555	1555	2026	1839	1856	1555
5-10	2618	1793	1793	2618	2158	2611	1852
10-15	2577	1970	1765	2577	2088	2659	1788
15-20	3052	2265	2091	3052	2494	2921	2125
20-25	2298	1581	1574	2298	1883	2380	1594
25-30	2771	2006	1898	2771	2249	2585	1929
30-35	1702	1267	1166	1702	1379	1714	1181
35-40	1772	1214	1214	1772	1440	1643	1230
40-45	1027	704	704	1027	832	1027	713
45-50	1029	705	705	1029	834	876	714
50-55	203	169	169	203	183	202	171
55-60	191	159	159	191	173	168	161
60-65	104	104	104	104	104	104	104
65-70	47	47	47	47	47	47	47
70-75	51	51	51	51	51	51	51
75-80	30	30	30	30	30	30	30
80-85	12	12	12	12	12	12	12
85-90	48	48	48	48	48	48	48
90-95	10	10	10	10	10	10	10
95-100	23	23	23	23	23	23	23
100-105	18	18	18	18	18	18	18
105-110	7	7	7	7	7	7	7
110-115	7	7	7	7	7	7	7
115-120	5	5	5	5	5	5	5
120-125	5	5	5	5	5	5	5
125-130	5	5	5	5	5	5	5
130-135	0	0	0	0	0	0	0
135-140	0	0	0	0	0	0	0

Table A-II presents impact speeds for all systems assuming operation and testing of the systems up to 140 km/h. The early activated AEB system has the highest number of avoided impacts (6850 cases for zero impact speed). Compared to the more speed restrictive assessment in Table A-I, AEB and early FCW systems achieve greater numbers of avoided impacts.

TABLE A-II

NUMBER OF IMPACTS PER 5 KM/H CATEGORY OF IMPACT SPEEDS ASSUMING BENEFIT UP TO 140 KM/H

Impact Speed [km/h]	No system	AEB late	AEB early	FCW audio-visual late	FCW audio-visual early	FCW brake pulse late	FCW brake pulse early
0	0	6180	6886	244	3965	868	6580
0-5	2270	1555	1555	2026	1839	1856	1555
5-10	2618	1795	1793	2618	2177	2611	1852
10-15	2577	1970	1767	2577	2091	2659	1807
15-20	3052	2265	2091	3052	2512	2921	2125
20-25	2298	1588	1575	2298	1887	2380	1603
25-30	2771	2008	1898	2771	2259	2585	1936
30-35	1702	1273	1166	1702	1385	1714	1190
35-40	1772	1239	1215	1772	1441	1643	1236
40-45	1027	724	704	1027	843	1027	717
45-50	1029	720	705	1029	837	886	724
50-55	203	147	140	203	168	201	144
55-60	191	137	131	191	162	176	136
60-65	104	76	71	104	87	94	77
65-70	47	35	32	47	42	48	36
70-75	51	41	35	51	44	47	38
75-80	30	23	21	30	26	27	23
80-85	12	11	9	12	12	19	10
85-90	48	35	33	48	40	41	34
90-95	10	8	7	10	9	12	8
95-100	23	16	16	23	19	22	16
100-105	18	13	12	18	15	16	13
105-110	7	6	5	7	6	7	5
110-115	7	6	5	7	6	7	5
115-120	5	4	4	5	4	5	4
120-125	5	4	4	5	4	5	4
125-130	5	4	4	5	4	4	4
130-135	0	0	0	0	0	0	0
135-140	0	0	0	0	0	0	0