

TEST PROCEDURES AND RESULTS FOR PEDESTRIAN AEB SYSTEMS

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ABSTRACT

Euro NCAP will start to test pedestrian Automatic Emergency Braking Systems (AEB) from 2016 on. Test procedures for these tests had been developed by and discussed between the AsPeCSS project and other initiatives (e.g. the AEB group with Thatcham Research from the UK). This paper gives an overview on the development process from the AsPeCSS side, summarizes the current test and assessment procedures as of March 2015 and shows test and assessment results of five cars that had been tested by BAST for AsPeCSS and the respective manufacturer.

The test and assessment methodology seems appropriate to rate the performance of different vehicles. The best test result - still one year ahead of the test implementation - is around 80%, while the worst rating result is around 10%. Other vehicles are between these boundaries.

INTRODUCTION

Automatic emergency braking systems for vehicle-to-rear-end-vehicle accidents are already in production since 2003 and have been considered in consumer testing by Euro NCAP since 2014. These look-ahead systems assess the risk of a collision with another vehicle and brake automatically if needed to mitigate or even avoid an accident.

Technology has made great progress in the last decade, and today also systems for avoiding or mitigating vehicle-to-pedestrian-accidents are within reach with first systems already on the market.

Systems that address pedestrian accidents are more challenging from a technology point of view due to three main reasons: pedestrians are able to change their heading almost immediately, making it difficult to correctly predict their movement; pedestrians are relatively small with only a little amount of metal, making it hard to detect and classify them with radar sensors, and last but not least, the majority of pedestrian accidents happen in cross-traffic situations. In longitudinal-traffic situations, directions of travel for both partners are parallel, while in cross-traffic they are perpendicular. Therefore, longitudinal accidents do happen as a function of velocity difference only. For cross-traffic accidents speed and starting position of the accident opponents have to match within small boundaries.

Pedestrian AEB¹ systems are being introduced into lower budget vehicle segments, but the technology is still relatively new. This poses the problem to define test and assessment criteria without knowing what the expected performance at the time of introduction will be. For a valid assessment methodology that also reflects real world accidentology it is of high importance to involve all stakeholders at an early state.

¹Automatic Emergency Braking

Proposed requirements for pedestrian AEB systems (and corresponding test procedures) were developed mainly by three initiatives: the seventh-framework-program-founded research consortium AsPeCSS², the initiative vFSS³ with German, Japanese and US-American manufacturers as well as independent research institutes) and the AEB-group (Thatcham Research, various manufacturers and suppliers, amongst others). The proposals then were considered by and discussed within Euro NCAP. A final set of test scenarios had been selected by the end of 2013, for extensive validation testing of the procedure (including repeatability and reproducibility considerations) in 2014. Pedestrian AEB systems will be rated from 2016 on.

This paper summarizes the proposals and concepts of the AsPeCSS-project and shows the scenarios that had been selected by Euro NCAP. An overview of the achieved rating according to Euro NCAP's preliminary rating scheme as of March 2015 will be given.

ACCIDENTOLOGY AND BOUNDARY CONDITIONS

Accidents involving passenger cars and pedestrians

Within the AsPeCSS project different European accident data sources (especially high level national data and in-depth accident data from Germany and Great Britain) were used to investigate the causations and backgrounds of road traffic accidents with pedestrians [Wisch 2013].

Results of the initiatives vFSS und AEB were reviewed and further extensive analysis was performed within AsPeCSS, focusing on the following topics:

- Aggregation of traffic accident data involving one passenger car and one pedestrian by accident type and impact configuration to Accident Scenarios
- Proportions of pedestrians by injury severity
- Darkness (i.e. frequency; accompanied visibility constraints due to weather conditions)
- Investigation of considerable accident parameters (i.e. pedestrian age; pedestrian impact points; crash reconstruction details such as driving and collision speeds of passenger cars, braking behaviour)
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As result of the accident data analysis seven accident scenarios have been identified which are shown in Table 1. This data does show that most collisions between one pedestrian and one passenger car are crossing conflict situations. Smaller proportions could be assigned to crash situations with obstructed view as well as to collisions where the pedestrian went along the road. Crashes while reversing or parking have been excluded from the dataset due to their minor relevance regarding current ahead looking and thus front mounted pedestrian protection systems.

Table 1 shows the proportions of the AsPeCSS accident scenarios (crashes between one passenger car and one pedestrian) for killed pedestrians only again based on national accident data from Great Britain and Germany. For the killed or seriously injured the highest average shares were established for scenario 1 (25%; crossing straight road, **near side**, no obstruction), followed by scenario 2 (20%; crossing straight road, **far side**, no obstruction), other scenarios (16%) and scenario 7 (15%, along straight road, no obstruction). For the total fatalities the highest average shares were established for scenario 2 (30%; crossing straight road, offside, no obstruction), followed by scenario 1 (23%; crossing straight road, nearside, no obstruction), scenario 7 (19%, along straight road, no obstruction) and other scenarios (17%).

In summary, accident scenarios 1, 2 and 7 were found as the three most important scenarios for car-to-pedestrian crash configurations (sum of weights concerning KSI⁴ is 60% and concerning fatalities is 72%) that may potentially be addressed by forward-looking integrated pedestrian safety systems. However, accident scenarios 3&4, 5 and 6 (KSI: 24%, Fatalities: 11%) also have a significant potential regarding future active pedestrian protection systems. Further, it was seen that more than half of the crashes which led to seriously injured pedestrians were assigned to darkness or low light conditions. This proportion increased to around three-quarters in case of killed pedestrians.

² including partners such as BMW, Toyota, PSA, TRW, Bosch, Autoliv, IDIADA, TNO, BAST

³ advanced forward-looking safety systems

⁴ KSI = killed or seriously injured

Table 1. AsPeCSS Accident Scenarios (A and B classify day (including twilight) and night times).

ID	Accident Scenario	% KSI Total (Day/Night)	% Fatalities Total (Day/Night)
1	Crossing straight road, near side, no obstruction	25 (15/10)	23 (8/15)
2	Crossing straight road, offside, no obstruction	20 (8/12)	30 (7/23)
3	Crossing at junction, near- or offside, vehicle turning across traffic	8 (5/3)	4 (3/1)
4	Crossing at junction, near- or offside, vehicle not turning across traffic		
5	Crossing straight road, near side, obstruction	9 (7/2)	4 (1/3)
6	Crossing straight road, offside, obstruction	7 (5/2)	3 (1/2)
7	Along straight road, no obstruction	15 (8/7)	19 (5/14)
Total		84 (48/36)	83 (25/58)

In addition, the following conclusion could be drawn from the analysis of the accident data:

- Higher count of car-to-pedestrian crashes in urban areas, but higher injury severity on rural roads,
- Elderly (65+ years) record the highest percentage of casualties killed or seriously injured,
- Winter months November, December and January show higher number of car-to-pedestrian crashes compared to other months.

Impact point

The impact point of the pedestrian on the front of the hitting vehicle is a key factor for the expected AEB system performance.

An evaluation of in-depth data from GIDAS⁵ shows that the impact point is actually distributed on the vehicle front, rather than being only in the vehicle center. In fact the occurrence of impacts at the outer regions of the vehicle front is higher than in the center. Impact point as function of vehicle velocity is shown in Figure 1 for running pedestrians that come from behind an obstruction. The lateral displacement of the impact point on the vehicle front is given in m, with 0 m corresponding to the vehicle centerline and with positive values towards the driverside. It can be seen that the impact is more likely to occur near the edge on that side where the pedestrian is coming from. Concluding from these observations, the impact point is a parameter that needs to be considered in the definition of test scenarios.

⁵ German In-Depth Accident Study, see www.gidas.org

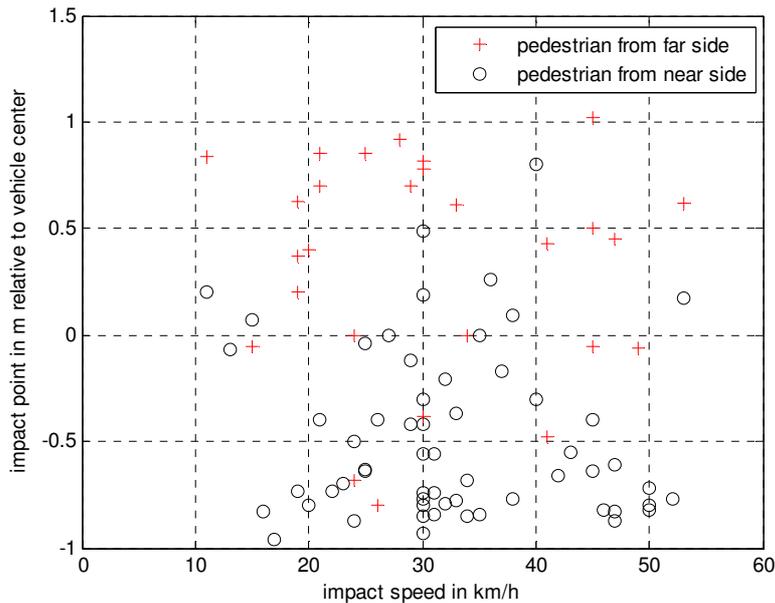


Figure 1: Impact point as function of vehicle travelling speed for running pedestrians appearing from behind an obstruction.

DEFINITION OF TEST SCENARIOS

Accident scenarios

Accident scenarios need to reflect real accident situations as good as possible. Since the accurate simulation of real accident situations in lab-testing is difficult and complex, characteristic parameters that have a significant impact on system performance have to be identified. Test scenarios then are defined using these characteristics.

For scenario definition, an accident kinematics model is developed using physical parameters like velocities, positions and starting times. In a first step, velocities are assumed to be constant, and in a second step, pedestrian detection timing and a brake logic were integrated. Using this model, the following parameters have been identified as most important for scenario definition:

- initial velocity of pedestrian and passenger car,
- impact point of pedestrian on the car front,
- start of pedestrian movement (timing) and total travel distance to impact point
- distance of obscuration (if applicable) to the passenger car path.

In addition, the following aspects need to be taken into account:

- test scenarios should reflect realistic accident situations as good as possible,
- test scenarios should be able to simulate various accident scenarios and not only those occurring most frequently,
- test scenarios should take estimated abilities of current and near-future AEB systems as well as current test tools (e.g. repeatability, contrast, light conditions) into account.

Test scenarios

Theoretical considerations and first test results showed that initial scenario definitions, especially a running child from behind an obstruction, are far too difficult for current and expected AEB systems.

In collaboration with other European initiatives, AsPeCSS developed the idea of distributing these difficulties (small child dummy, obstruction and running dummy) into more than one scenario in order to be able to better assess and compare system performances.

The test scenarios have been improved based on the AsPeCSS test results shown in this paper and on the test results generated within the AEB group and together with Euro NCAP for better comparability of vehicles, see Table 2. The dummy speed in the child scenario has been decreased to 5 km/h, and the different impact points (a fact that is quite important according to accident figures) are tested with a walking, unobscured adult dummy. Higher pedestrian walking speeds are transferred to a scenario with an adult dummy coming from the far side - the dummy will be easily visible long before the impact in this case. Low dummy speeds might be difficult for certain sensor systems and will be tested in the form of an entrance test; the same goes for low vehicle speeds (10; 15 km/h) since the required sensor viewing angle becomes rather large for high ratios of dummy speed to vehicle speed.

Table 2. Current scenario definitions for Euro NCAP pedestrian tests.

Scenario	Running adult	Walking adult	Walking adult	Walking child
Parameter				
Denomination	CPAF	CPAN25	CPAN75	CPCN
Pedestrian speed	8 km/h	5 km/h	5 km/h	5 km/h
Dummy type	Adult	Adult	Adult	Child
Dummy initial position	Far side	Near side	Near side	Near side
Vehicle speeds	20-60 km/h	20-60 km/h	20-60 km/h	20-60 km/h
Obscuration	No	No	No	Yes
Impact point	50 % (Center)	25% (Nearside)	75% (Nearside)	50 % (Center)
Weighting	1	1	1	1

ASSESSMENT METHODOLOGY

Boundary conditions

Pedestrian travel speeds are generally much lower than car speeds [Tiemann, 2010]. But pedestrians can still comfortably avoid passenger car accidents just fractions of a second prior the collision. This is particularly true for accidents with impact on the near-side edge of the vehicle front and is less critical for impact points near the far-side edge. Determining for the achieved speed reductions is the time when full braking commences (which corresponds to a lateral distance of the pedestrian to the vehicle path). This brake timing limits the achievable speed reduction (which is a function of initial speed and deceleration). The ability of the brake system to increase the brake pressure and deceleration (maximum brake jerk) is another factor, as well as is the delay time between brake command and brake actuation.

If the pedestrian is hidden behind an obscuration and therefore is at first not freely visible for the vehicle's sensor system, the detection and classification time has a major impact on the entire system performance.

The derivation of performance boundaries in this paper is done based on an ideal braking system and a point-shaped pedestrian. A full investigation of the effects of real brake systems (e.g. increase of brake force) and finite size of pedestrians is published in [Seiniger, 2013].

The selected scenario configuration reflects the frequent case of a pedestrian crossing perpendicular to the vehicle. For full avoidance, the stopping distance s_{Stop} of an ideal vehicle is a function of initial velocity v_{Vehicle} and deceleration a_x

$$s_{\text{Stop}} = \frac{v_{\text{Vehicle}}^2}{2 \cdot a_x} \quad (1)$$

The quantity "Time-To-Collision" [Winner, 2011] is more reasonable for describing these situations than the stopping distance since it depends on the brake timing rather than a fixed distance. For the crossing pedestrian, it can be simplified to:

$$TTC = \frac{x_{\text{Vehicle}}}{v_{\text{Vehicle}}} \quad (2)$$

The unit of TTC is the second. TTC is the time until the collision occurs if all speeds were held constant and in this case it is used to describe discrete points in time.

The TTC (when braking needs to start) for full avoidance is the combination of (1) and (2):

$$TTC_{\text{Stop}} = \frac{v_{\text{Vehicle}}}{2 \cdot a_{x,\text{Vehicle}}} \quad (3)$$

The essential quantity for speed reduction in pedestrian AEB systems is the time available for braking - which is in general the TTC at which the pedestrian is considered "critical". Real AEB systems will consider a pedestrian critical when it is near to the vehicle path (e.g. within a second) and on collision course.

The pedestrian's impact point on the vehicle front is the second essential quantity determining possible speed reduction. Pedestrians with a high probability for an impact on the near-side of the vehicle will become critical much later than those with an impact on the far-side of the vehicle, because those latter ones do travel within the path of the vehicle for a significant amount of time.

Balancing these criteria with the acceptable rate of false-positives then is the task of the vehicle manufacturer's philosophy, considering also product liability, customer acceptance and the likes, see for instance [Lübbe, 2013].

A real challenge for any AEB system are pedestrians coming from behind an obscuration near the side of the road. In this case, the total time available for detection, classification, decision and braking is limited by the time the pedestrian is visible.

Relevance of test speed for traffic safety

The assessment methodology for pedestrian AEBs needs to be in line with that established already for vehicle-vehicle AEB systems [Euro NCAP 2013]. For each scenario, tests with increasing test speeds are proposed.

In principle a linear assessment of speed reductions as measured in the individual test cases seems to be reasonable: 0% of "assessment units" for no speed reduction, 100% assessment units for full avoidance. The unified result of a test suite then depends on the weighting of the individual test speeds (within a test scenario) and the weighting in-between the scenarios.

The dose-response-model [Wisch 2013] is an established methodology for the weighting of speed reduction within a test scenario (= for different tested speeds). This methodology defines weighting factors by multiplying injury probability and accident occurrence frequency for all speeds. The factors then correspond to the "risk" and measure the relevance of a given test speed. Due to practicality reasons, the risk curve is approximated with 1 to 3 points, see Figure 2.

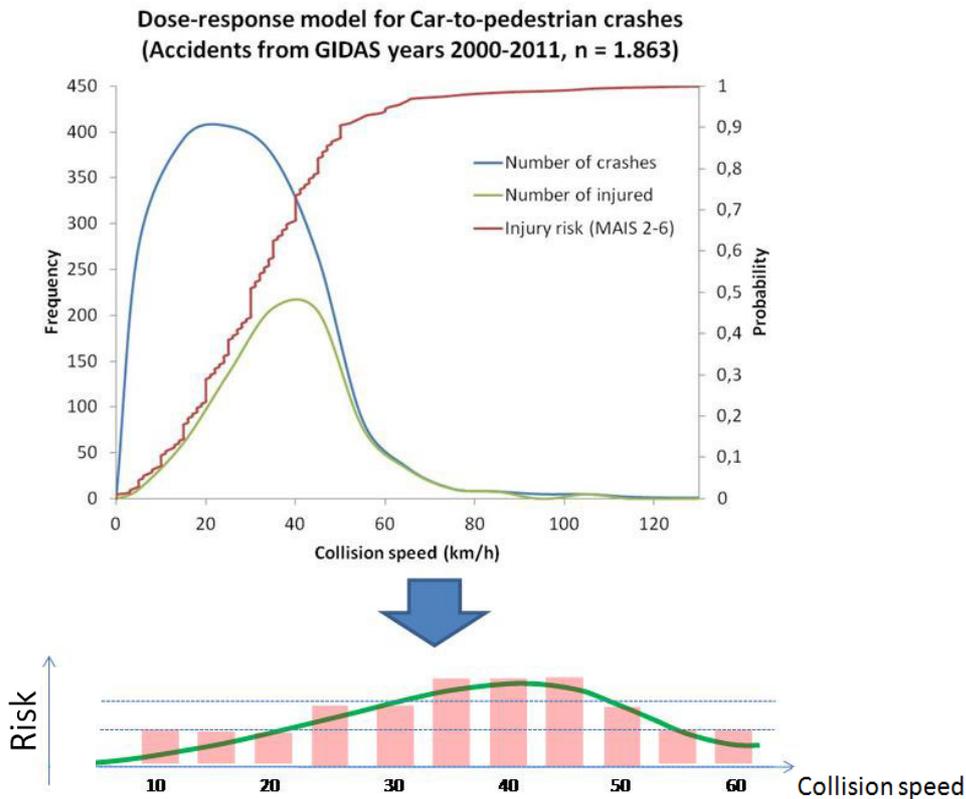


Figure 2: Derivation of in-scenario weighting from accident velocity and injury risk.

While the vehicle speed scale as defined from the AsPeCSS consortium runs from 10 to 60 km/h, tests and theoretical considerations have shown that an AEB intervention for low vehicle speeds is difficult to achieve due to the required high sensor viewing angle. Since additionally the risk level up to 20 km/h is still relatively low, Euro NCAP selected to exclude 10 and 15 km/h vehicle speed from performance testing; however it is necessary that the vehicle does at least show an AEB activation in these test speeds, in the form of an entrance test that needs to be passed for further assessment. The same goes for slower dummy speeds of less than 5 km/h.

In the previous section it has been laid out that full avoidance for high vehicle speeds is not possible: the pedestrian becomes a critical target so late that the time available for braking is not sufficient for the vehicle to come to a complete stop. Due to this, Euro NCAP has selected to award full score for high speeds (>45 km/h) if the speed reduction at the individual test is more than 20 km/h, and the test is conducted only if the preceding test was passed. The scoring is shown Table 3.

Table 3. Rating parameters.

Index “k”	1	2	3	4	5	6	7	8	9
Test speed	20	25	30	35	40	45	50	55	60
Points	1	2	2	3	3	3	2	1	1
Sliding Scale	1	1	1	1	1	0	0	0	0
Pass/Fail	0	0	0	0	0	1	1	1	1
Method	<ul style="list-style-type: none"> Sliding scale: ratio of speed reduction and initial speed 					<ul style="list-style-type: none"> Pass for speed reduction > 20 km/h Test only executed if previous test speed is passed 			

In a mathematical formulation, the rating result per scenario will become:

$$Rating = \sum_{k=1}^{k=n} SC(k) \cdot Points(k) \cdot \frac{v_{x,red,k}}{v_{x,0,k}} + PF(k) \cdot Points(k) \cdot \langle v_{x,red,k} - v_{x,red,min} \rangle^0 ,$$

with the vectors “Sliding scale SC”, “PassFail PF”, “Points” and “ $v_{x,red,min}$ = minimum speed reduction = 20 km/h” as defined in *Table 3*, and using the Föppl-parenthesis “ $\langle \rangle^0$ ” which becomes 0 for results less than zero and 1 otherwise.

TEST TOOLS

Testing pedestrian AEB systems requires a pedestrian dummy as well as an apparatus that is able to move the dummy with a necessary accuracy.

Requirements for the dummy are as follows:

- appears like a human for the vehicle sensor system,
- impactable without significant damage to the vehicle under test (especially damage to the AEB system's sensors),
- durability: the possibility to conduct a high number of tests with impacts without significant change in the physical properties.

AsPeCSS uses a dummy as specified by the vFSS group. A detailed description of the dummy characteristics can be found in [Lemmen, 2013]. This dummy proved to appear close to a human in extensive verification testing with various test vehicles, and the current version is able to take over 100 impacts and does not damage the vehicle under test. This dummy has also been selected by Euro NCAP as an appropriate static dummy. A dummy with animated legs is currently developed by industry and might be selected as the official test dummy; this decision was not taken as of March 2015.

Dummy movement is achieved using a transportable platform system which has sufficient position accuracy due to its tooth belt drive (Figure 3) and that carries the dummy by means of magnets. Driving robots for accurate longitudinal and lateral vehicle control were used in all experiments in this paper. The specifications of the dummy propulsion system meet the requirements set by Euro NCAP in their preliminary test protocol at the time of writing.



Figure 3: Test setup with adult dummy, platform, belt drive and light switch system.

DRIVING EXPERIMENTS AND RESULTS

Figure 4 shows speed reductions for vehicles A to D, distinguished between dummy type (child/adult), dummy speed, obstruction, propulsion system and desired impact point. All tests were conducted by BAST. Vehicles A, B and C were tested for the AsPeCSS project; vehicles D and E were tested in cooperation with the respective manufacturer.

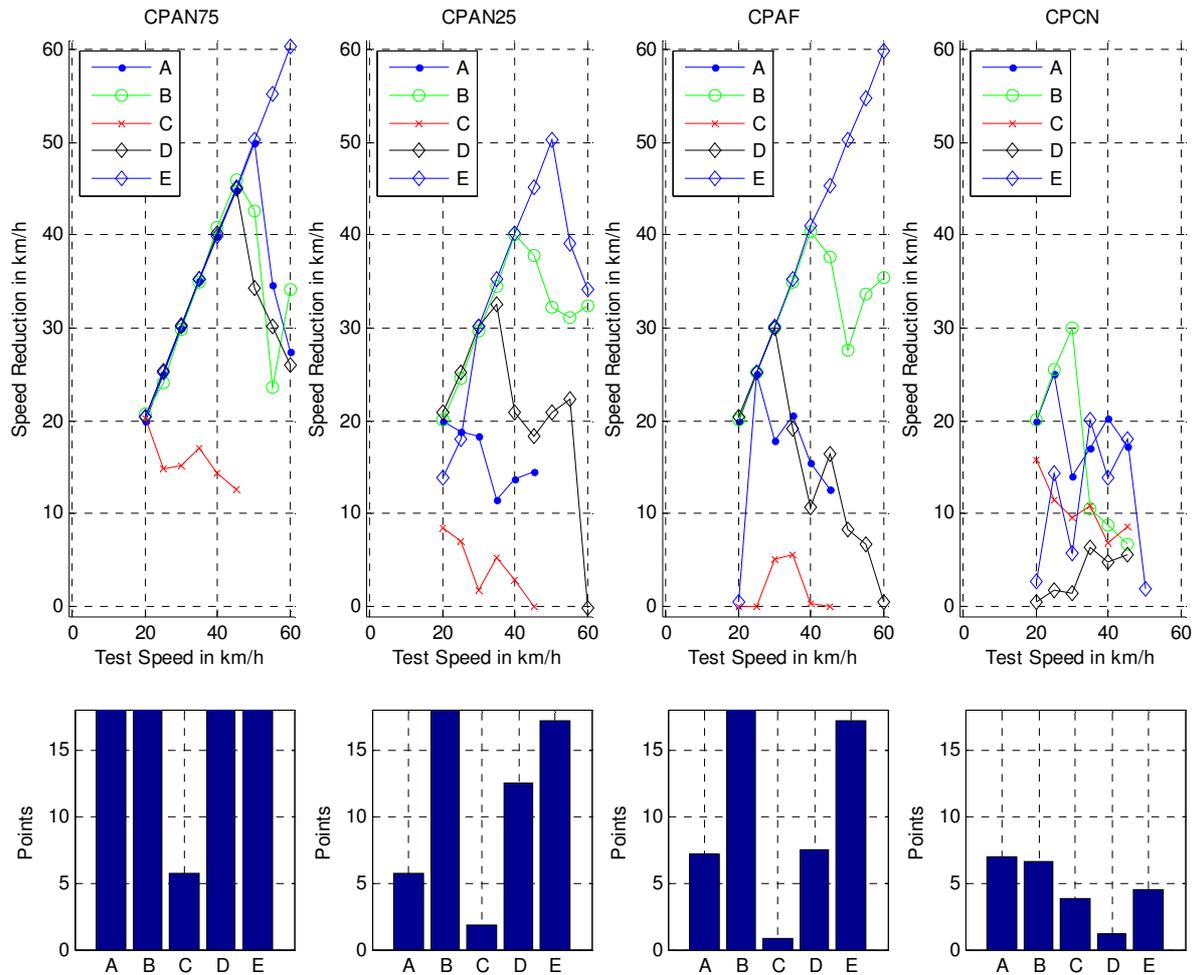


Figure 4: Speed reduction (upper diagrams) and points awarded (lower diagrams) per vehicle and scenario. CPAN75/25= Car-to-Pedestrian Adult Near side, impact point 25% or 75%, CPAF= Car-to-Pedestrian Adult Far side, CPCN= Car-to-Pedestrian Child Near side.

Note that the vehicles A to D were tested more than once per test speed. For this analysis, the highest speed reduction per test speed has been picked. Vehicle E was a prototype vehicle, all others are production vehicles.

This overview gives an impression on the range of results to be expected for the first tests in 2016. All but one vehicle do achieve maximum rating in the Adult near-side 75%-scenario, which is from a technical perspective considered to be the easiest. The same setup with a 25% impact point is more difficult: since the dummy is located more to the right⁶ throughout the whole experiment, the required sensor viewing angle is higher. The

⁶ For right hand traffic

dummy will also enter the zone where a braking intervention is justified at a later time. Two of the vehicles still achieve almost full score in this scenario.

An adult approaching from the far side at running speed is difficult as well: for lower speeds, the required viewing angle becomes relatively large, and the dummy enters the zone where braking is justified at a late time as well. Results for this scenario are comparable: vehicles B and E again achieve almost full score.

The most critical scenario from a technical perspective is the obstructed child: the dummy appears relatively late, so there is little time available for detection, classification and braking. The results show that none of the tested vehicles is able to achieve a rating of more than 7 points. This might change when vehicles will be equipped with quicker brake systems.

SUMMARY

The AsPeCSS project did define accident scenarios for pedestrian AEB systems. These scenario proposals then were discussed with other initiatives, the outcome of these discussions was the basis for Euro NCAP pedestrian test scenarios and assessment method.

Several vehicles have been tested and rated according to the Euro NCAP test and assessment method, within the AsPeCSS project and by BAST in cooperation with the respective vehicle manufacturer. While the 75% near-side adult scenario does not pose much difficulty to most of the systems, the near-side 25% and far-side running adult scenarios are far more difficult. Only two out of the five vehicles achieve almost full score.

None of the tested vehicles is able to achieve more than 7 points (=40% of the available points) in the running child scenario - a major technology innovation might be required before vehicles are able to perform equally well in this scenario.

LITERATURE

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