A METHODOLOGY TO DERIVE PRECISION REQUIREMENTS FOR AUTOMATIC EMERGENCY BRAKING (AEB) TEST PROCEDURES

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ABSTRACT

AEB Systems are becoming important to increase traffic safety. Test procedures in testing for consumer information, manufacturer self-certification and technical regulations are used to ensure a certain minimum performance of these systems. Consequently, test robustness, test efficiency and finally test cost become increasingly important.
The key driver for testing effort and test costs is the required repeatable accuracy in a test design - the higher the accuracy, the higher effort and test costs. On the other hand, the performance of active safety systems depends on time discretization in the environment perception and other sub-systems: for instance, typical sensors supply information with a cycle time of 50 - 150 ms. Time discretization results in an inherent spread of system performance, even if the test conditions are perfectly equal.
The proposed paper shows a methodology to derive requirements for a test setup (e.g. test repeats, use of driving robots, ...) as function of AEB system generation and rating method (e.g. Euro NCAP points awarded, pass/fail, ...). While the methodology itself is applicable to AEB pedestrian and AEB Car-Car scenarios, due to the lack of sufficient test data for AEB Car-Car, the focus of this paper is on AEB pedestrian scenarios.
A simulation model for the performance of AEB Pedestrian systems allows for the systematic variation of the discretization time as well as test condition accuracy. This model is calibrated with test results of 4 production vehicles for AEB Pedestrian, all fully tested by BASt according to current Euro NCAP test protocols.
Selected parameters to observe the accuracy of the test setup in case of pedestrian AEB is the calculated impact position of pedestrian on the vehicle front (as if no braking would have occurred), and the test vehicle speed accuracy. These variable was shown in real tests to be repeatable in the range of ± 5 cm and ± 0,25 km/h, respectively, with a fully robotized state of the art test setup.
The sensitivity of AEB performance (measured in achieved speed reduction as well as overall rating result according to current Euro NCAP rating methods) towards discretization and the sensitivity of performance towards test accuracy then is compared to identify economic yet robust test concepts.
These comparisons show that the available repeatability accuracy of current test setups is more than sufficient for today's AEB system capabilities. Time discretization problems dominate the performance spread especially in test scenarios with a limited pedestrian dummy reveal time (e.g. child behind obstruction, running adult scenarios with low car speeds). This would allow to increase test tolerances to decrease test cost.
A methodology which allows to derive the required tolerances in active safety tests might be valuable especially for NCAPs of emerging countries that do not have the necessary equipment (e.g. driving robots, positioning units) available for the full-scale and high tolerance EuroNCAP active safety procedures yet still want to rate active safety systems, thus improving the global safety.

INTRODUCTION

AEB Systems are becoming important to increase traffic safety. Test procedures in testing for consumer information, manufacturer self-certification and technical regulations are used to ensure a certain minimum performance of these systems. Consequently, test robustness, test efficiency and finally test cost become increasingly important.
One of the major discussion points during the implementation of AEB test procedures was the required precision of test execution. The initial scenarios (as implemented in 2014) had been longitudinal scenarios. Both vehicles (target as well as vehicle under test) move on parallel - ideally identical – tracks. The main parameters which drive test cost are the precision of both vehicles' speeds, and the lateral displacement between the vehicles at all times.

Things become more complicated for scenarios where the target brakes during the test conduction: the initial longitudinal displacement between both vehicles should ideally be constant, and the target deceleration process, characterized by brake ramp and target deceleration, needs to be repeatable.
Finally, lateral traffic accident situations such as the proposed pedestrian scenarios require an exact match between positions of both target and vehicle under test during the constant speed phase of the test execution; otherwise the AEB system is presented with a different situation. A parameter representing this match of positions is the theoretical impact position of the target on the vehicle-under-test's front, calculated for a situation without automatic braking.
Testing always introduces uncertainties into how good these parameters can be maintained. The more complex the equipment is, the lower become the tolerances, and the higher is the precision of testing. Goal of this paper is to identify the relation between tolerances and expected certainty of results (e.g. speed reduction for the pedestrian AEB systems).

Research Questions and Methodology

The goal of this paper is to identify the relation between precision in test execution and variability in test results for AEB pedestrian test setups. Variability is influenced by test execution precision, but also by limitations inside current AEB systems.

- How does the test execution precision in AEB pedestrian tests influence the variability in speed reduction and overall rating?
- How do technical limitations in pedestrian AEB systems influence the variability in speed reductions and overall rating?

These questions will be answered with a simulation model for AEB pedestrian tests. The model allows to introduce tolerances in the test execution and as well as technical limitations (e.g. sensor angles, processing times, time discretization). A model for AEB Car-Car braking scenarios is developed as well, however there is not sufficient data for model validation.
Model input besides the mentioned tolerances and technical simulations is the test condition, output is the achieved speed reduction This model is parameterized and validated using all possible test data. Validation is successful if the simulation results match the test track results sufficiently well. Sufficiently well in this case means that the observed effects (e.g. variations, peak avoidance speeds, tendencies of speed decrease) can be replicated.
Results of the sensitivity investigations then are presented as plots overall rating variation as function of the varied parameter.

SIMULATION MODEL

The simulation model is loosely based on the model presented in [Seiniger, 2013]. It simulates the braking process of a vehicle, including brake delay time, deceleration ramp and deceleration levels. In [Seiniger, 2013], the model determined the brake time using certain paradigms (e.g. when the accident cannot be avoided by driver or pedestrian). The updated model now determines the appropriate brake time using AEB logic, sensor and visibility characteristics. These parameters had been derived from test data, gained within the AsPeCSS project [ASPECSS, 2014] and in BASt tests for manufacturers. Brake time determination differs whether the simulated test is an AEB pedestrian test or an AEB Car-Car test.

Generic Simulation Model Structure

Main part of the simulation model is the calculation of speed reduction as function of brake parameters, brake time and vehicle initial speed. The brake time is determined either by brake strategy (in cases where target detection is not a limiting factor) or by the remaining time before the impact after sensor detection (in other cases). The target reveal time (only applicable for pedestrian AEB simulation) is not only limited due to obstructions, but in some situations also by the sensor field-of-view and / or additional processing time. The overall structure of the simulation model is shown in Figure 1.

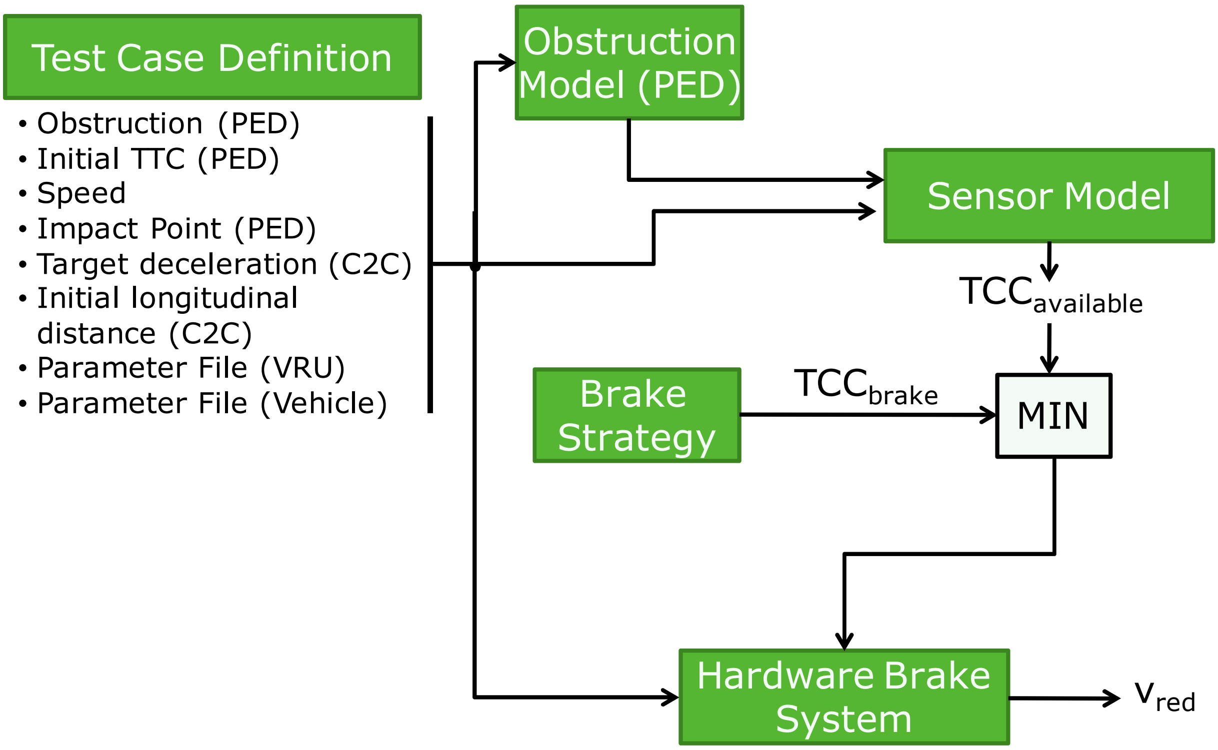

Figure 1. **General structure of the simulation model (PED = pedestrian, C2C = Car-Car, MIN = minimum value of $TTC_{available}$ and TTC_{brake} is selected)**

Sensor and obstruction models for Pedestrian AEB tests

The concept behind the obstruction and sensors model block in case of pedestrian AEB is depictured in Figure 2. For Field-of-view investigation, the angular position of the target towards the sensor is evaluated. The sensor model calculates the time at which the target enters the sensor field of view, if this is a limiting factor, and the obstruction model calculates the time at which the target appears from behind the obstruction, if this is a limiting factor. In both cases, the percentage of the target that is required for proper detection is a parameter of the simulation. Other parameters within the obstruction and sensor model block are the size and position of the obstruction with respect to target and vehicle-under-test, the sensor field-of-view angle, the sensor longitudinal position with respect to the vehicle front, and the required sensor processing time, after the target becomes visible.

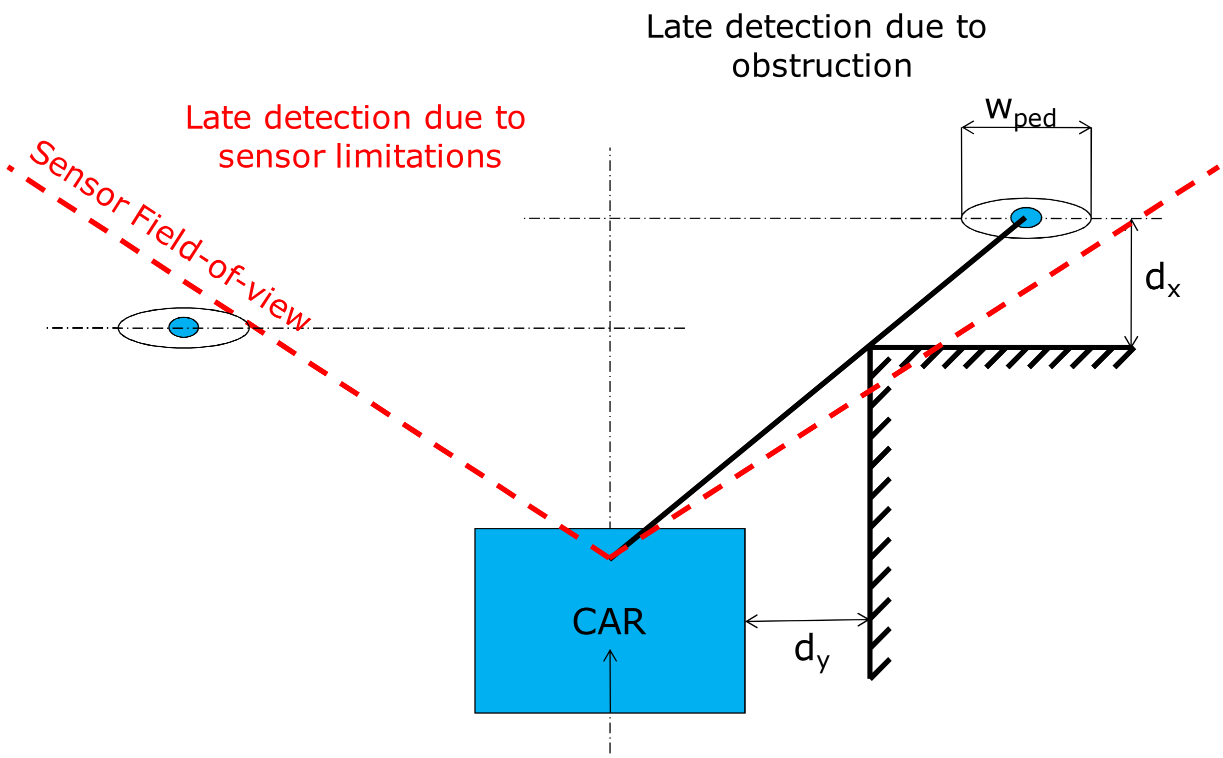

Figure 2. **Concepts behind the sensor model and obstruction model blocks. Variables are the lateral position of obstruction with respect to the vehicle d_y, the longitudinal position of the obstruction with respect to the pedestrian target d_x, the size of the pedestrian target w_{ped}.**

An important parameter that is responsible for variations in measured speed reduction even with perfectly constant test parameters is the sensor sample rate. All sensors sample their data at discrete times, and usually the interval between sampling times is constant. Assuming that the AEB system brake decision requires at least one measurement (=sample) to verify that brake conditions exist, this final verification is available with a maximum variability equal to the sample rate, see Figure 3.

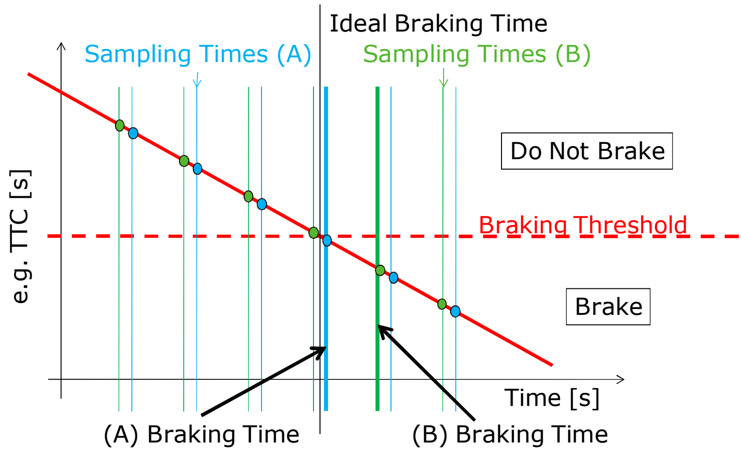

Figure 3. **Sensor time discretization creates brake timing variations: an example using TTC as threshold for brake timing. The ideal brake timing would be at the point where TTC crosses the threshold. In case A, blue, a new measurement (dots on the TTC line, accompanied by vertical lines) is available just after TTC crosses the threshold, so almost no additional time delay due to sensor time discretization is introduced. In case B, green, a measurement occured just before the TTC crossed the threshold, so the new measurement is**

available almost one complete sample time after TTC has crossed the threshold - and thus, almost one complete sample time is introduced as the additional time delay. Since the sampling process starts at system start far before the test, the probability for any time delay between no delay and full sampling time should be equal.

Brake Strategy for Pedestrian AEB Systems

Identification of brake strategy requires some system identification from the available test data. Various strategies are used by the in total 5 cars that were available for validation. An appropriate criterion to characterize the threat of collision is the value Time-To-Collision TTC [Winner, 2011]. TTC is the quotient of relative distance in direction of travel Δx and relative speed Δv:

$$TTC = \frac{\Delta x}{\Delta v}.$$

The variable TTC describes the current time that is left until a collision occurs if speeds of target and vehicle-under-test do not change.

Test data shows that all vehicles use a threshold for the lateral position of the target, a threshold for the Time-To-Collision value (TTC), or both, and in some cases, different thresholds for different pedestrian speeds have been observed. Note that a collision will occur in all of the defined test cases, if no braking is initiated.

Brake Strategy for Car-Car AEB Systems

The most relevant and demanding Car-Car test scenario with respect to required accuracy is the braking scenario: two vehicles initially travel at an equal and constant speed, with a constant longitudinal distance, until the target vehicle decelerates. The target vehicles' deceleration level and the time until this fully developed deceleration is achieved are test parameters. In this case, the variable TTC as described above cannot be used, since it does not take the target deceleration into account. A more appropriate variable is the "enhanced TTC" ETTC [Winner, 2011]:

$$ETTC = \frac{\sqrt{\Delta v^2 + 2 \cdot D_{rel} \cdot \Delta x} - \Delta v}{D_{rel}},$$

introducing the relative deceleration between both vehicles D_{rel}. Test data shows that ETTC characterizes the brake timing relatively well: start of braking consistently occurs at a constant ETTC threshold (only test data from one vehicle test series used).

The sampling time effect on time variability should be relevant for these tests as well, but sensor detection usually is not a limiting factor since the target vehicle is in full sensor field of view during the whole experiment.

Hardware Brake System

The model for the hardware brake system calculates the achieved speed reduction for a given TTC of commanded braking, relative velocity and initial conditions, taking a constant delay time after brake command, constant brake jerk and maximum deceleration into account. All calculations are numerical.

Additionally to calculation of speed reduction, this block also evaluates whether the accident is avoided or not: for pedestrian AEB tests, in some cases pedestrians gain enough time to clear the path due to the brake intervention, and these situations then are counted as avoided accidents.

Model Parameter List

Table 1 shows a full set of the available model parameters for AEB pedestrian as well as AEB Car-Car.

Table 1. **Simulation model parameter list**

Parameter	Category	Description	Typical value
TTC_AEB_DESIRED	Brake Strategy	TTC Threshold for brake onset	1 s
DIST_PEDESTRIAN	Brake Strategy	Lateral distance threshold between pedestrian and vehicle center at brake onset	2.2 m

ADJUST_DIST_RUNNING	Brake Strategy	Increase DIST_PEDESTRIAN by this factor for running pedestrians (8 km/h rather than 5 km/h)	1.2
ETTC_BRAKE	Brake Strategy	ETTC Threshold for brake onset in Car-Car scenarios	1
TTC_DELAY	Sensor Characteristics	Time that is required from first sensor measurement until proper target recognition	0.2 s
ADJUST_T_DELAY_SPEED	Sensor Characteristics	Higher relative speeds will increase the detection time, because optical flux / differences between two images become to great.	YES (for camera)
T_DELAY_SPEED	Sensor Characteristics	Speed threshold after which detection time increases	35 km/h
T_DELAY_HIGH_SPEED	Sensor Characteristics	Factor for detection time increase	2
ADJUST_T_DELAY_DISTANCE	Sensor Characteristics	Higher distance will increase the detection time for stereo cameras, because stereo effect vanishes for far objects	YES (stereo camera)
T_DELAY_DISTANCE	Sensor Characteristics	Distance	15 m
T_DELAY_HIGH_DISTANCE	Sensor Characteristics	Factor for detection time increase at high distances	2
SENSOR_ANGLE	Sensor Characteristics	Field of view-angle of the most relevant sensor	20°
TARGET_PROPORTION	Sensor Characteristics	What proportion of the target needs to be in sight for proper target recognition	50%
SENSOR_X_POS	Sensor Characteristics	Most relevant sensor longitudinal position with respect to vehicle front	0 m (for RADAR)
FRAMERATE	Sensor Characteristics	Most relevant sensor frame rate	10 Hz
T_DEAD_AEB	Brake Hardware	Delay between brake command and brake onset	0,35 s
JERK_AEB	Brake Hardware	Maximum rate of deceleration increase	20 m/s^3
A_MAX_AEB	Brake Hardware	Maximum achievable deceleration	6 m/s^2
W_VEHICLE	Vehicle	Width of vehicle	1.85 m
W_PED	Target	Width of target (e.g. length of bicycle target, width of pedestrian dummy)	0.6 m (Pedestrian Dummy)

MODEL VALIDATION

AEB for Pedestrians

The quality of the simulation model can be estimated by comparing simulation results with test data. For the validation process of the pedestrian AEB model, test data from four different vehicles is available. All four vehicles have an own parameter set. Parameters have been identified from the test data as well.
Simulations and test results for four vehicles and four scenarios are shown in Figure 4.

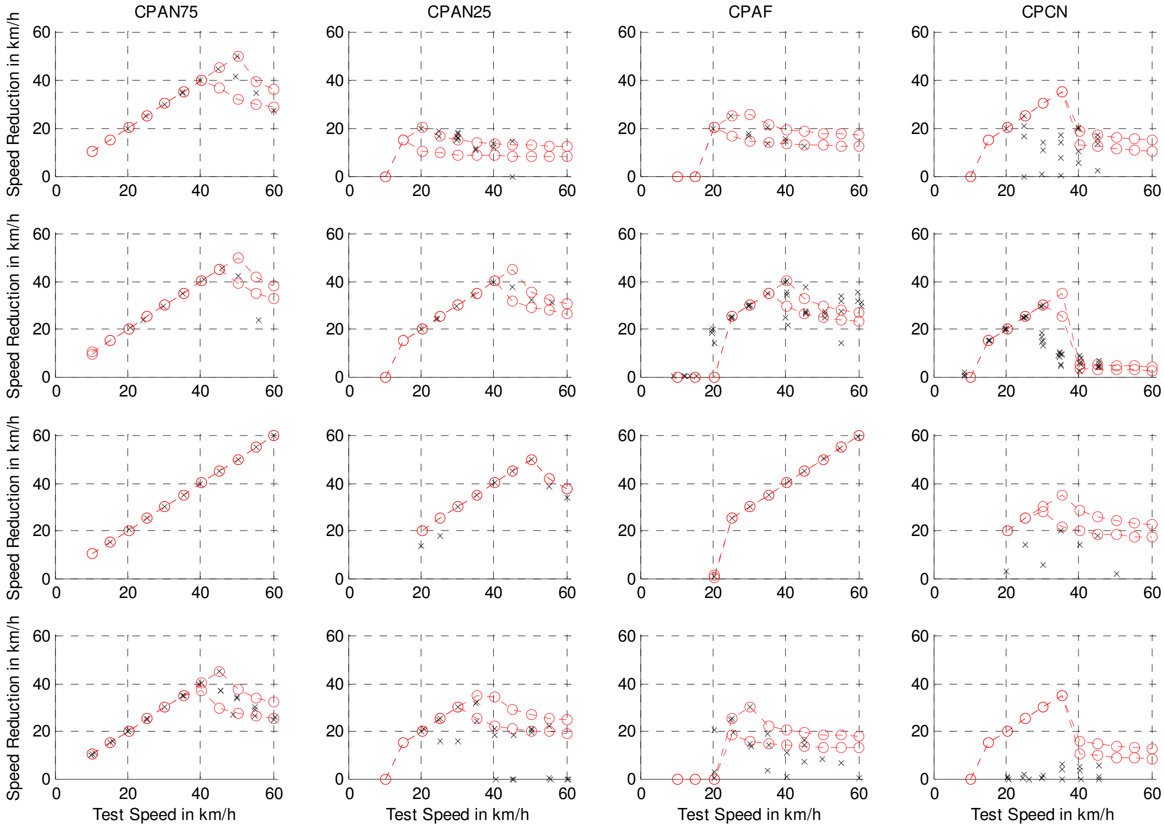

Figure 4. **Comparison of measured speed reductions (black crosses) and simulation results (red circles) for pedestrian AEB tests. Scenarios according to Euro NCAP pedestrian scenarios, CPAN75=Car-Pedestrian-Adult-Near Side-75%, CPAN25=Car-Pedestrian-Adult-Near Side-25%, CPAF=Car-Pedestrian-Adult-Far Side, CPCN=Car-Pedestrian-Child-Nearside. Two different plots for simulation results are available: one for no time delay due to sensor sampling time (in general the upper line), and one for full time delay due to sensor sampling time.**

Simulation results match test data sufficiently well: they reproduce the general tendencies of the test data like peak avoidance speeds, minimum activation speeds, and result variability. This leads to the conclusion that the model structure is valid and the model can be used for the projected sensitivity studies.

SENSITIVITY ANALYSIS

Methodology for sensitivity analysis

The goal of this paper is to identify the influence of tolerances in test execution and variability in technical systems on the test result in AEB tests. A simulation model with parameter sets for four different real world vehicles is used to answer these questions. The baseline is ideal test execution according to current Euro NCAP scenarios for pedestrian AEB and a sensor processing factor of 0.5 (meaning additional delay of half the sensor sampling time). Based on this, selected parameters (one at a time) are modified to represent inaccuracies in test setup. The results are given in one combined plot per vehicle and scenario, resulting in an array of 16 plots.

These 16 plots in Figure 5 show much detail about the required test precision, but for an overview, an integral criterion is needed: Euro NCAP's assessment method is such an appropriate integral criterion.
Euro NCAP awards different points per test speed, corresponding to the real world relevance of that specific speed (for details, see [Seiniger 2015]). Full points for lower speeds are awarded for full speed reduction using a sliding scale. Full points for higher speeds (>45 km/h) are available 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 2.

***Table 2.* 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
PassFail	0	0	0	0	0	1	1	1	1
Method	• Sliding scale: ratio of speed reduction and initial speed					• 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:

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

with the vectors "Sliding scale SC", "PassFail PF", "Points" and "$v_{x,red,min}$ = minimum speed reduction = 20 km/h" as defined in Table 2, and using the Föppl-parenthesis "$< \ >^0$" which becomes 0 for results less than zero and 1 elsewise.

Results

Test case definition, color coding for the plots and rating results relative to each baseline condition per vehicle is shown in Table 3.

***Table 3.* Parameter variations, coding as shown in *Figure 5* and overall rating results compared to baseline in %, for vehicles A to D**

Variant No.	Variation	Color	Marker	Rating A	B	C	D
1	Baseline	Black	.	100%	100%	100%	100 %
2	Earlier Detection, no influence of sampling time	Red	+	107%	101%	104%	104 %
3	Later Detection, full influence of sampling time	Red	O	93%	99%	98%	90%
4	Impact Point 5 cm towards Dummy	Blue	O	96%	99%	99%	95%
5	Impact Point 20 cm towards Dummy	Green	O	84%	91%	99%	75%
6	Impact Point 5 cm away from Dummy	Blue	+	104%	101%	101%	102 %
7	Impact Point 20 cm away from Dummy	Green	+	133%	101%	102%	120 %
8	Test speed 1 km/h below nominal speed	Cyan	+	104%	101%	105%	105 %
9	Test speed 1 km/h above nominal speed	Cyan	O	98%	96%	102%	101 %

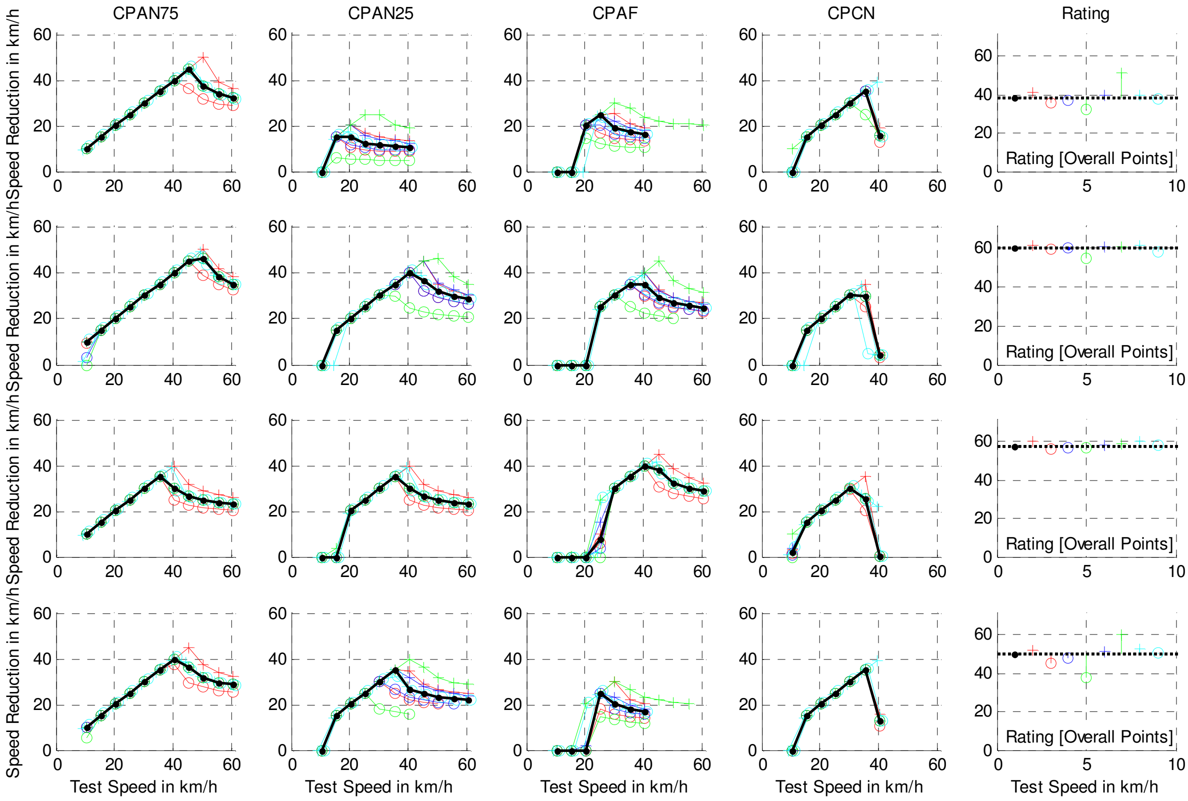

Figure 5. **Results for parameter variations, one vehicle per row. Shown is the achieved speed reduction for each test case from *Table 3* with the appropriate color coding, as well as the overall test result using the Euro NCAP assessment method.**

These results show that the most relevant parameter with respect to test execution precision seems to be the variation in impact point location. While a shift in impact point of 5 cm (as required according to current Euro NCAP protocol) changes the overall results by maximum +4% and -5%, a shift by 20 cm affects the results by a tremendous +33% or -25%. Speed variations during the test, even up to 1 km/h plus or minus (which is four times the value allowed according to the current Euro NCAP protocol) have an effect comparable to the allowed 5 cm impact point shift. Assumed timing variations due to sensor sampling by ± half of sampling time affect the rating slightly more than the allowed 5 cm impact point shift.

These three parameters have been used for a further detailed study of their influence towards the overall rating result per vehicle, see Figure 6. All three plots are based on the baseline, only the selected parameter has been varied.

General tendencies are as expected:

- Moving the impact point away from the position where the pedestrian comes from generally gives AEB systems more time for detection, classification and braking, thus increasing the overall score. The score is more sensitive towards the impact shift for vehicles with generally lower score.
- Increasing the vehicle speed slightly allows for earlier pedestrian detection in critical scenarios for a given sensor angle, but also slightly takes away potential for speed reduction. Both effects seem to compensate each other in the overall rating result, and this is true for all four vehicles.
- Shifting the sensor detection time within an assumed sample rate to earlier values allows for an earlier target detection and thus braking decision which increases the overall rating. The effect of sensor time shift is different for the various vehicles.

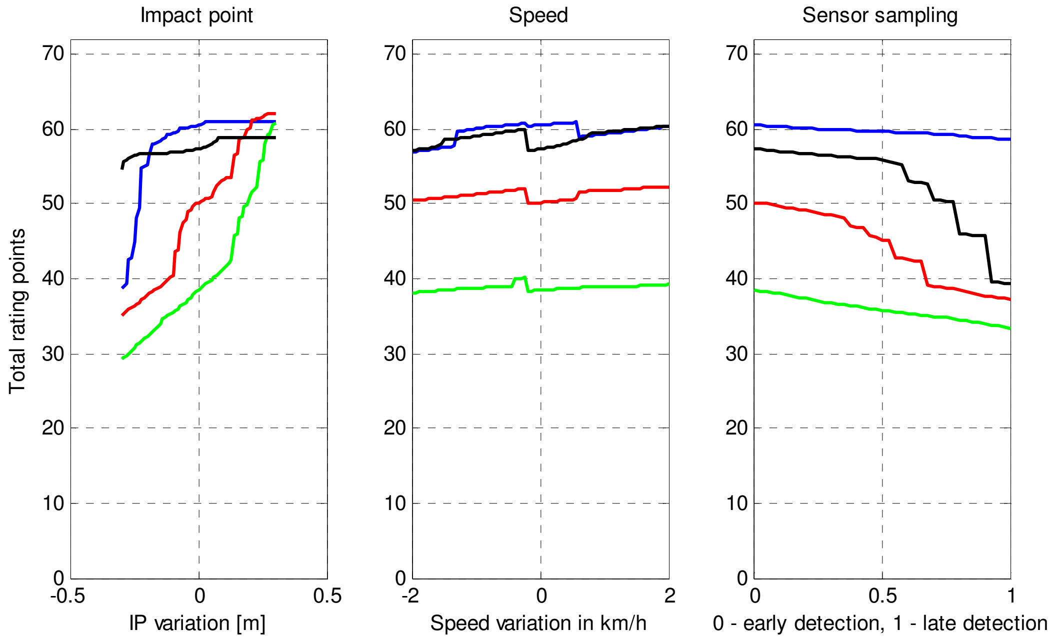

Figure 6. **Sensitivity of overall rating result towards variations of impact point (with respect to the side where the pedestrian comes from), vehicle speed and sensor sampling timing.**

Derivation of required test precision

The most sensitive parameter that needs to be controlled by the test lab is the lateral variation of the impact point. If the test lab is able to maintain the impact point within a range of ± 5 cm, the results in the worst have a variability of ± 2 points of the Euro NCAP rating scheme. For ± 10 cm, this increases to ± 10 points. Note, however, that these values are worst case, assuming a systematic shift of the impact point in the direction of worse test results. In reality, the error will rather be stochastic and vary towards both directions - thus, the influence of the impact point error to overall test result will be much lower.
The other relevant parameter, the vehicle test speed, has a neglectable influence towards the overall score, even if it is varied by ± 2 km/h with respect to the desired test speed.

Consequences

Test experience shows that human drivers are able to maintain one variable (vehicle speed, lateral offset etc.) in acceptable ranges, but are not able to control two variables at the same time. If the test setup is able to synchronize the dummy movement with unprecise but constant vehicle speeds, the tests could be driven by human drivers alone and still allow for an acceptable accuracy with regards to the test result. The influence of vehicle sensor timing issues to the overall test result is then comparable to the error from test conduction.
Since in this case driving robots are not necessary anymore, the test cost can be greatly reduced.

SUMMARY

Goal of this paper was to show a methodology to derive accuracy requirements for a test setup for AEB systems, with focus on AEB pedestrian systems. A simulation model allows to vary relevant parameters and estimate the influence of the given parameters towards speed reduction and overall test result (according to the Euro NCAP assessment method).
The simulation model has been calibrated and validated against AEB pedestrian test data from four different production vehicles.
Sensitivity studies show that the most relevant parameter that needs to be controlled by the test lab is the lateral impact point of the pedestrian dummy on the vehicle-under-test's front. It should be in the range of ± 5 cm. Test vehicle speed variations in the range of ± 2 km/h have an neglectable influence towards test outcome.

Since test vehicle speed just needs to be held constant, but not exactly on a defined value, only one control channel for vehicle control is needed. In this case, it is anticipated that a combination of human driver and test setup (dummy propulsion system) with compensation for speeds and lateral offsets is sufficient to achieve an acceptable test execution precision.

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