A METHOD FOR DEVELOPING AEB SYSTEMS BASED ON INTEGRATION OF VIRTUAL AND EXPERIMENTAL TOOLS

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ABSTRACT

This paper proposes an enhanced methodology for AEB system development combining road testing, in-door laboratory testing, hardware-in-loop testing and simulations. The application of the modeling part of methodology is demonstrated using an OEM vehicle system. The physical AEB system is subjected to the AEB City and AEB Inter Urban test series as proposed by Euro NCAP. The test series are executed in a laboratory environment. Simulation models are generated and validated against the experimental data from these test series. System sensitivity is evaluated using a parameter variation study and validated simulation models.

1. INTRODUCTION

Several car manufacturers have introduced autonomous braking systems with the aim of mitigating the effects of accidents or even preventing accidents from occurring. The benefit of these autonomous braking systems to vehicle safety is acknowledged by legislative authorities and consumer bodies, which has led to several initiatives to legislate or reward these new safety technologies. The European Commission is mandating autonomous emergency braking (AEB) systems for commercial vehicles from 2013. Euro NCAP will include AEB systems in their rating system from 2014. Euro NCAP has proposed a standard test protocol representing the most important scenarios for urban (AEB City) and non-urban (AEB Inter-Urban) conditions. However, a wider set of traffic scenarios must be considered during AEB system development to guarantee reliable and robust functioning in real-world traffic. It is too costly and time-consuming to test all these real-world scenarios on a test track or public road. This issue will grow further with the next generation AEB safety that will include vulnerable road user safety (AEB Pedestrian). Reproducible and controlled scenario conditions are essential to achieve complete evaluation during system developments. This paper proposes an enhanced methodology for AEB system development combining road testing, in-door laboratory testing, hardware-in-loop testing and simulations. The paper will provide an overview of the entire development methodology for AEB systems, and will address in more details the role of indoor lab testing and the validation and usage of CAE models.

Section 2 gives an introduction of the simulation environment and a description of the AEB vehicle modeled that is used throughout the study. Next, in section 3, the AEB laboratory experiments used for the system assessment are presented, and the validation of the simulation model is shown. Section 4 presents three parameter variation studies that are executed based on the validated AEB simulation modeled from section 5. Finally, section 6 contains concluding remarks as well as an outlook to future studies.

2. CAE MODEL DESCRIPTION

2.1 PreScan

The CAE tool that is used in the methodology is PreScan software [1]. PreScan is physics-based simulation platform that is used in the automotive industry for development of Advanced Driver Assistance Systems (ADAS) that are based on sensor technologies such as radar, laser/lidar, camera and GPS. PreScan is also used for designing and evaluating vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication applications. PreScan can be used from model-based controller design (MIL) to real-time tests with software-in-the-loop (SIL) and hardware-in-the-loop (HIL) systems. (see Figure 1).

The tool allows to build various traffic scenarios using a database of road sections, infrastructural components (trees, buildings, traffic signs) and road users (cars, trucks, cyclists, pedestrians as well as balloon cars). Weather conditions (rain, snow, fog)

and light circumstances can be modeled as well. The vehicle models can be equipped with one or more different sensor types. A Matlab/Simulink interface enables users to design and verify algorithms for data processing, sensor fusion, decision making and control as well as the re-use of existing Simulink models such as vehicle dynamics models. PreScan can be used for model-based controller design (MIL), real-time tests with software-in-the-loop (SIL) and hardware-in-the-loop (HIL) systems [2, 3, 4, 5].

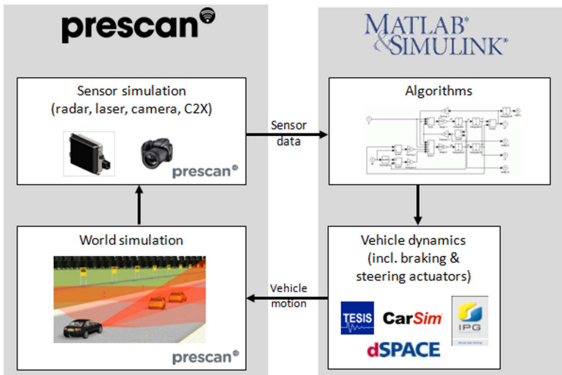

Figure 1. The co-simulation principle of PreScan and Matlab/Simulink

2.2 CAE model of an Autonomous Emergency Braking System (AEBS)

System Description: This paragraph describes the design, usage, and testing of the AEBS model built in PreScan and Simulink. The main principles of the system model (sensoring and system deployment policies) are based on the functionality of the current systems available on the market. The AEB system model uses the information from long-range radar and the host vehicle to identify the potential collision risk with the objects detected by the radars (Figure 2).

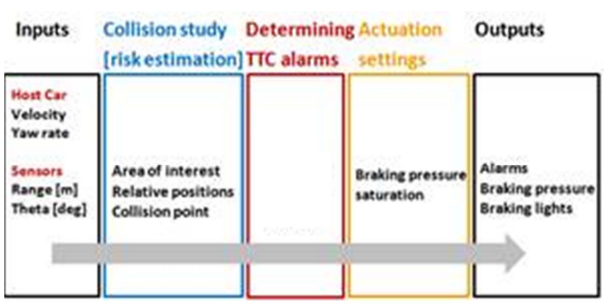

Figure 2. Information and decision flow in the AEBS controller model.

The calculation is based on the information about the area of interest (direction of the car), relative position and direction of the moving or stationary object. Based on this information, the collision point is estimated and object is classified as collidable. The parameter Time To Collision (TTC) is calculated and the controller determines the warning alarms to prompt the driver based on the TTC values and the relative velocity difference between the host vehicle and the target object. The warning is deployed earlier if the relative velocity difference is larger and vice versa. At this point, the system waits for the driver to intervene: either by releasing the accelerator or pressing the brakes.

Based on the driver reaction, appropriate pressure is set in the braking actuation block and the controller output is sent to the actuators: braking system and braking lights. The following steps are taken by the AEBS:

- warns driver to act in order to prevent accident
- intervenes when driver reacts through;
  - Autonomous **partial braking** when driver releases the accelerator
  - Autonomous **full braking** when driver pushes the brakes

System Modeling: Host Car with AEBS: The AEB system model is a Simulink model (available as part of the PreScan software release) that is placed on a PreScan car model, representing a generic passenger car with driving performance typical for mid-class car, and a driver model. The braking model is based on the PreScan internal vehicle dynamics model and it can generate maximum 0.85G of braking deceleration. Figure 3, shows the placement of the radar sensor on the car; lower left bumper.

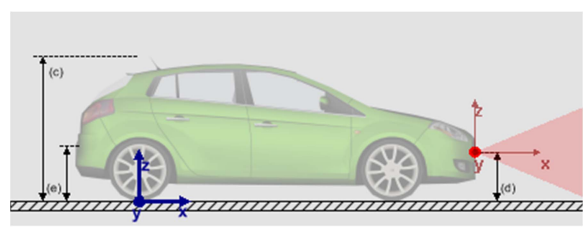

Figure 3. PreScan Model of the car with LRR

The TIS (Technology Independent Sensor) models of sensors available in PreScan database were used to represent the long range radars with the following settings: Long range radar (LRR), 200m range, 10deg FoV.

System Modeling: Driver Model: The modeled AEBS system requires driver intervention for brake deployment. There was a need to model the driver

reactions to the warning system for AEB system operation. Estimation of the driver reaction delay to system warning is an active research area [6]. Traditionally the driver reaction time estimation studies have been carried out on driving simulators [7]. In the ASSESS project a similar study was carried out [8] to quantify the driver reaction time on two different simulators. In the aforementioned study, although the experimental designs were based on the same concept, different results were observed, illustrating the difficulty in obtaining robust reaction times to a warning. The study concluded that it is very difficult to robustly define a generic driver reaction that is applicable to a range of different scenarios.

PreScan simulation environment was utilized to estimate the driver reaction times to PreScan warnings for the tested scenarios. A Matlab model for estimating the driver reflexes and response delay times, based on the Driver in the Loop Experiments carried out using Logitech Hardware, was implemented. A total of 11 participants were tested and their response times to driver warning were noted down and used as inputs to the applied driver model. The resulting data are presented in Table 1.

Table1. Resulting average data for human driver reflexes and response delay times

	First Reaction Time: Time to Release Accelerator [s]	**Second Reaction Time: Time to Press Brake [s]**
Average of 11 participants	0.59	0.11

<u>System Modeling: Target Balloon Car</u>: The target object is a PreScan model of a draft version of the Euro NCAP balloon target cover that is being pulled by a truck. The PreScan driver model controls the trajectory for the truck and consequenly for the target object.

<u>PreScan Scenarios</u>: The pre-crash scenarios considered rear-end collision to vehicles in city and inter-urban surroundings. In each scenario the car is equipped with autonomous emergency braking system model. In Figure 4, the CAE model is shown. The scenario model represents a straight suburban road, side objects, host car and other traffic participants.

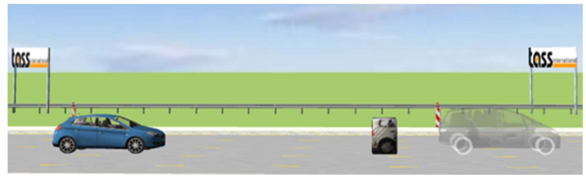

Figure 4. PreScan represented scenario with the vehicle under test and the balloon target.

The modeled test scenarios have been selected to in line with the scenarios for AEB City and Inter-Urban as are currently foreseen in [10, 11] The represented scenarios, Table 2, cover three variations of the basic case Car-to-Car Rear end (CCR) collision;

- Test T1 (CCRm): Approaching a slow moving object
- Test T2 (CCRb): Approaching an object decelerating constantly
- Test T3 (CCRs): Approaching a stationary object

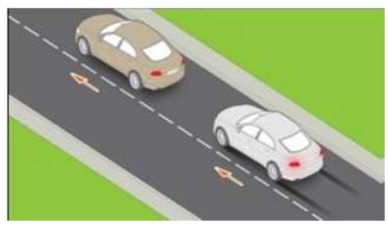

Figure 5a. Slower Lead Vehicle

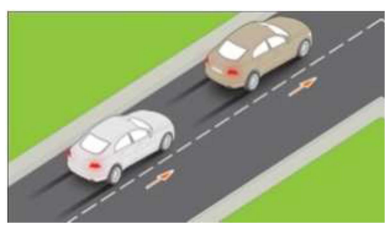

Figure 5b. Lead Vehicle Decelerating

Figure 5c. Lead Vehicle Stopped

Table2. PreScan Represented Scenarios

Scenario	Host Car speed [km/h]	Target Car speed [km/h]	Target Deceleration [m/s]	Initial Distance [m]
Test T1	50-80	20	-	75
Test T2	50	50	-2,-6	12,40
Test T3	10-80	0	-	120

Limitations of the CAE model: An average vehicle has been identified for this study and the standard vehicle dynamics model available in PreScan software has been adopted. The model has the following assumptions;

1. linear suspension model;
2. ideal friction conditions (dry road, new tyres)
3. No Anti-lock braking system;

The controller represents the basic functionality of an AEBS controller. The detailed architecture of the controller might not be a true representation of the advanced functionality of the AEB System of the tested vehicle.

3. MODEL VALIDATION

3.1 Laboratory experiments

The TNO VeHIL laboratory allows for testing an active safety system (sensors, ECU, actuators, HMI and vehicle motion) in controlled and safe laboratory conditions [4, 5]. For the pre-crash evaluation of the AEB system a new setup is used, that has been developed and evaluated in the EU ASSESS project [9]. This is based on movement of a balloon target that can impact the test vehicle in frontal scenarios. In this setup, the moving balloon target is guided by a floor mounted cable system that accurately controls the motion of the target, as shown in Figure 6.

The balloon target (different targets are possible) is accelerated or decelerated in driving direction of the vehicle whit speeds up to 80 kph and with varying overlaps. In a safe, repeatable and non-destructive manner a scenario is evaluated until the actual moment of impact (TTC=0), measuring speed reduction, braking profiles and system timings.

Figure 6. VeHIL setup with PreCrash setup with balloon target

In different recent investigations, most importantly the work done as part of the EC ASSESS project, the VeHIL AEB test method is evaluated. In the ASSESS study the VeHIL Pre-Crash test setup was benchmarked with different scenarios, different AEB vehicle systems, different balloon targets and different outdoor and indoor pre-crash test methods in Europe. The results and conclusions of this work are described in ASSESS [9]. In this paper the earlier ASSESS evaluation work done is extended with a a range of AEB Car to Car Rear scenarios with the Euro NCAP target (Figure 7).

Figure 7. Used balloon target in for lab testing

3.2 Model correlation

The results for the tests represented in PreScan and VeHIL were compared. Table 3 presents the average of the percentage correlation levels for the three type of CCR tests carried out in VeHIL lab and then represented in PreScan, as discussed in section 2.To simplify the analysis, the vehicle was compared for the completely autonomous functionality of the AEB system under discussion;

initiation of the driver warning. Each test was conducted three times to provide input for the repeatability and reproducibility analysis for the VeHIL testing facility.

Scenario	**Warning -** Time To Collision [s] **% Correlation PreScan**
Test_T1	91%
Test_T2	60%
Test_T3	94%
Average:	**81%**

Above table presents the correlation levels between VeHIL and PreScan test results. Tests T1 and T3 show a correlation level of about 90%. Test T2 shows lower levels of correlation due to the simplified braking profile that was adopted for the PreScan simulations of the target car.

4. PARAMETER VARIATION STUDY

A simulation study was conducted to investigate the sensitivity of certain parameters (braking pressure, sensor noise and road curvature) on the performance of the AEB system under test. The primary objective was to demonstrate the application of the aforementioned methodology for developing AEB systems.

4.1 Brake Pressure Variation Study

AEB combines advanced driver assist systems and premium electronic stability control to rapidly decelerate the vehicle with or without driver intervention if a crash is determined to be inevitable. The Brake Pressure Variation (Maximum Applied Deceleration) tests aim to evaluate the effectiveness of the AEBS under different deceleration conditions. The rearward impact scenario is modeled, the car travels at the speeds of 30-100 km/h, the target car moves at a speed of 20 km/h and the braking conditions are varied for each scenario. The AEB system generates a warning at the risk of collision with the slowly moving target vehicle. It is assumed that the driver applies brakes, at which the system applies the maximum possible deceleration (tested variable parameter). The behavior of the host car, if it manages to avoid the collision or not, is noted down for different deceleration conditions for different test speeds for the host car.

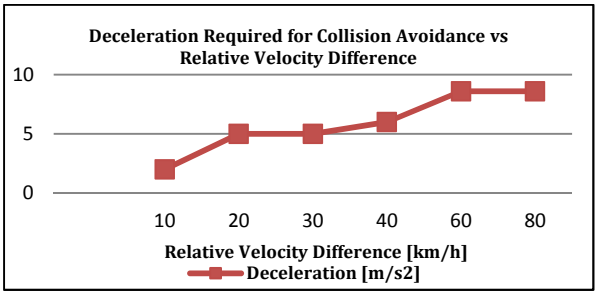

Figure 8. Maximum Deceleration Required for Collision Avoidance vs Relative Velocity Difference

It was observed that for a relative velocity difference of 10 km/h a deceleration of 2 m/s2 was enough to avoid the collision. Similarly, for a relative velocity difference of 40 km/h a deceleration of 6 m/s2 was sufficient to be able to completely avoid collision with the target vehicle and so on. Figure 8 presents the summary of the brake pressure variation study. It is observed that there is an increasing trend between the minimum deceleration required, for the host car, to avoid collision with reference to the relative velocity difference between the host and the target vehicles. This information may be utilized as a starting point for the development of an adaptive AEB system, especially important for the City Traffic Scenarios in which sudden application of a full braking may create a collision risk for the vehicles following the host car.

4.2 Sensor Noise Variation Study

The Sensor Noise Variation tests aim to evaluate the effectiveness of the AEBS under different environmental clutter and noise conditions. The rearward impact scenario is modeled, the car travels at the speed of 50 km/h, the target car moves at a speed of 30 km/h and the sensor noise conditions are varied for each scenario. The AEB system considered in this paper is based on a long range radar, as discussed earlier. The radar has a range of 200m, a horizontal field of view of 10 degrees and an update rate of 100Hz. The AEB system generates a warning at the risk of collision with the slowly moving target vehicle. It is assumed that the driver applies brakes, at which the system applies the maximum possible deceleration. The behavior of the host car, the deviation in the TTC for driver warning is noted down for different sensor noise conditions for the host car. PreScan, using additive Gaussian Noise in

the reflection path for the TIS sensor is used to model the environmental clutter typical for Radar sensors.

The sensor noise is varied between 0.5 – 5 deg in azimuth and between 0.5 – 5m in range for the TIS. We observed that the sensor noise in azimuth alone doesn't affect the performance of the system however, for the noise in range greater than 1m, figure 9, there is a large variation in the calculations of the TTC measurements for driver warning. The Sensor Noise Variation study indicates the effects of the environmental noise on the performance of the AEB System. This study may be utilised to improve the logic of the controller and increase its robustness.

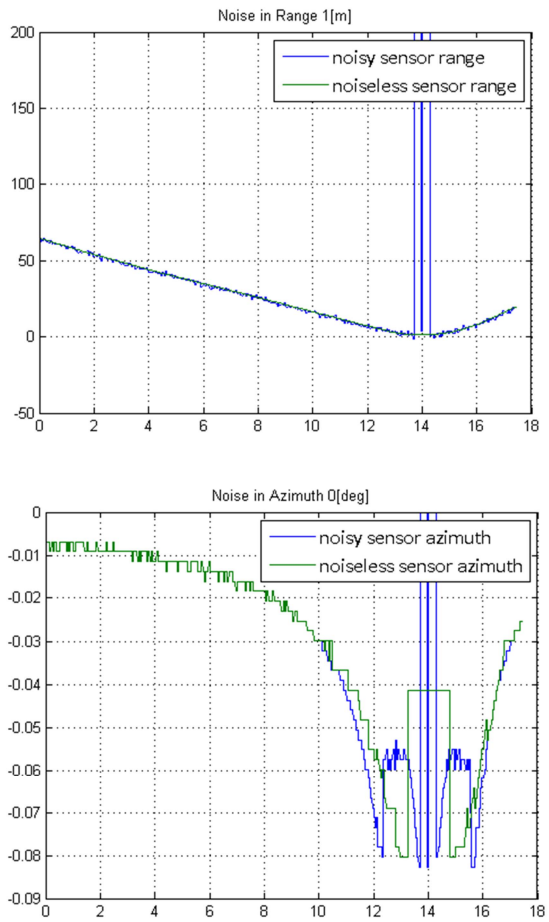

Figure 9. Fluctuations in the Range and Azimuth measurements for the TIS sensor with an additive reflective noise in Range for 1m

4.3 Road Curvature Variation Study

The Road Curvature Variation tests aim to evaluate the effectiveness of the AEBS under different road curvature condition scenarios. The rearward impact scenario is modeled, the car travels at the speeds of 30-100 km/h, the target car moves at a speed of 20 km/h and the road curvature conditions are varied for each scenario. The AEB system generates a warning at the risk of collision with the slowly moving target vehicle. It is assumed that the driver applies brakes, at which the system applies the maximum possible deceleration). The behavior of the host car, if it manages to avoid the collision or not, is noted down for different road curvature conditions for different test speeds for the host car. Three variations for the rearward impact scenario, slowly moving target vehicle are modeled (The worst-case (curvature 150, speed 100km/h) lateral acceleration was noted down to be 5.2 m/s2.).

Experiment	Host Car speed [km/h]	Target Car speed [km/h]	Initial Distance [m]	Radius of Curvature [m]
Curved_500	30-100	20	200	500
Curved_250	30-100	20	200	250
Curved_150	30-100	20	200	150

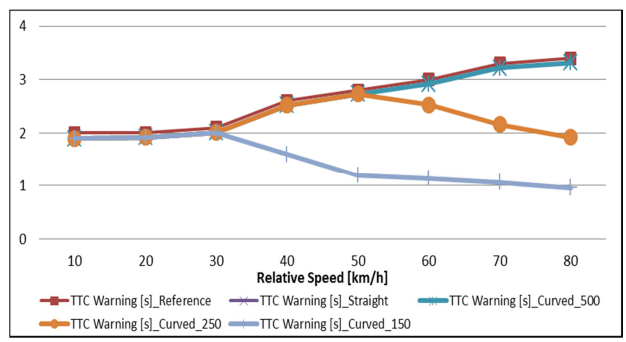

Figure 10. Comparison of TTC for Driver Warning for Road Curvature Variation

Figure 10 presents the comparison of calculated TTC for driver warning for various road curvature scenarios with the reference TTC driver warning values, straight road scenario, for different relative speed conditions. It is observed that the tested system deviates from the desired (reference) performance for a relative speed of about 60km/h when the road curvature is 250m. Similarly, a deviation in the desired system behavior is observed at a relative speed of about 30 km when the road curvature is 150m. The testing shows that the modeled AEB

system may not behave as desired for the higher relative speed scenarios on curved roads. This is due to the limited field of view (FOV) for the LRR utilized in the system.

4.4 Results

The PreScan-Matlab simulation of the collision scenario results in the actuation of the host vehicle's AEB system that deploys ***driver warning*** and slows down the car from initial driving velocity to either full stop or lower collision velocity through partial or full braking. The measured variables include the TTC for the driver warning, driver reactions and the collision speed in km/h (if the collision is not avoided) which are then compared with the laboratory experiment test results. The performance of the system can be analyzed using the pop-up alarm cascade, display panel for the AEBS experiments that provide information on the reduced collision speed as a result of system deployment, vehicle velocity profile, vehicle deceleration profile and the TTC timings for each system deployment stage. It may be noted that the user can modify the simulation and system settings: maximum braking pressure, indicator ON/OFF, throttle opening, driver response, driver reaction and brake system delay values.

6. CONCLUSIONS

The presented work shows the use of validated virtual models and laboratory experiments for the design and development phase of AEB systems. The simulation tooling is capable of assessing the effects of the performance of all AEB system components (such as sensors, object detection & interpretation algorithms and vehicle dynamics control algorithms) on the safety performance of the complete ADA system. In the parameter variation study, the effects of various system settings, scenario conditions and also different noise levels of the sensor signals are investigated. The presented parameter variation study shows the benefit of using validated CAE models in the early stages of development in order to (i) avoid identification of design errors in the prototyping phase, and the (ii) selection of relevant critical scenarios for test track testing. VeHIL shows its potential, as a next step to the simulation study, to determine the real system/sensor/controller performance using a series of high quality experimental measurements in the controlled laboratory environment. The advantage of the use of the PreScan-VeHIL tool-chain is that the performance of the system components can be verified in the earlier stages of the development cycle already before the system prototyping phase begins.

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