DEVELOPMENT OF A PRE-CRASH SYSTEM USING THE VEHIL TEST FACILITY

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ABSTRACT

Pre-crash systems (PCSs) use environment and vehicle dynamics sensors to improve the effectiveness of passive safety devices by activating them before a collision occurs. The autonomous character of these intelligent vehicle systems, required to anticipate dangerous traffic situations, as well as the combination of new hardware and software technologies make the design extremely complex.

This paper presents an evaluation of a PCS using the VEhicle Hardware-In-the-Loop (VEHIL) test facility. The prototype system utilizes a long-range forward-looking, installed for adaptive cruise control systems, for activation of a reversible belt retractor. The VEHIL laboratory enables testing of intelligent vehicle systems in a hardware-in-the-loop environment, where only the relative motion between host and target vehicle is reproduced. The accuracy of VEHIL test setup made sensor validation and control system testing much easier and more flexible. It appeared to be useful for fine-tuning sensor post-processing algorithms, path prediction algorithms, and activation times.

In addition, the radar system is modeled with the PRESCAN simulation tool, which enables simulation of environment sensors in a virtual environment. The simulated sensor output can be used for development of sensor post-processing, sensor fusion and control algorithms. Also other design aspects like sensor positioning and overall system architecture can be considered.

INTRODUCTION

In the US, the number of all, injury and fatal crashes has remained somewhat constant over the last decades, as shown in Figure 1. However, when looking at the number of accidents per miles traveled, the number has been decreasing, as shown in Figure 2. This is primarily due to improvements in passive safety, such as seat belts and airbags.

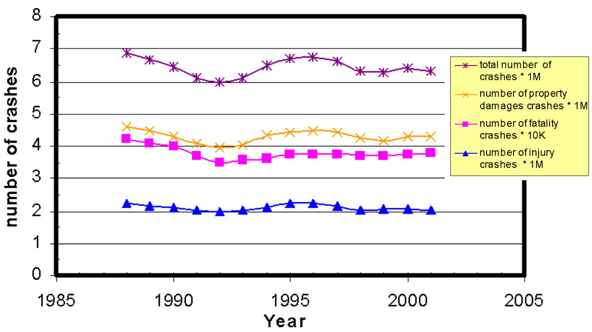

Figure 1. Absolute accident statistics [NHTSA, 2002].

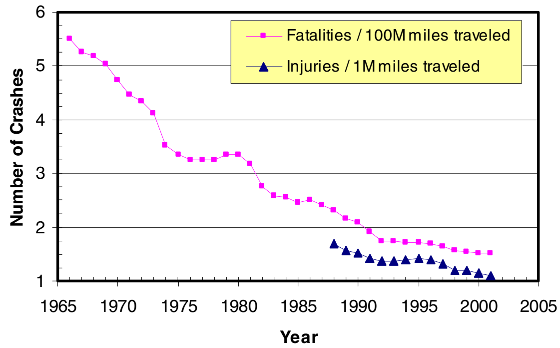

Figure 2. Accident statistics per mile traveled [NHTSA, 2002].

Nowadays, the recent trend in the safety community is to integrate both active and passive safety so further reduction can be achieved. Examples of active safety are vehicle control systems that use environment sensors like radar to improve the driving comfort and traffic safety by assisting the driver in recognizing and reacting to dangerous traffic situations. The effectiveness of *passive* safety restraints can be increased by using the time between initial recognition of an imminent crash and the actual impact to tune the restraint systems and position the occupants.

This potential for improving occupant safety has stimulated research on so-called pre-crash systems (PCSs) [Alessandretti, 2002] [Moritz, 2000] [Tokoro, 2003], and its recent market introduction [Honda, 2003], [Schöneburg, 2003]. A PCS is a system that uses environment sensors, vehicle dynamics sensors, and electronic control functions to mitigate the crash severity by deploying passive and/or active safety measures *before* a collision occurs.

The development of a PCS is a critical process, because of the necessary high reliability of the system. Failure or inappropriate activation of an automatic safety system simply cannot be tolerated. Therefore, automatic deployment of a belt pre-tensioner should be executed if, and only if, a crash is imminent and unavoidable. Using sensor data on the path of the obstacle and the estimated time-to-collision, it can be predicted with a certain probability if a collision is imminent, and that a collision cannot be avoided anymore by either braking or steering.

Due to the high reliability requirements, a PCS needs to be thoroughly tested. A PCS test is however very safety-critical, since an actual collision is necessary to reproduce the operating conditions. Obviously, because of the inherent safety risks and prototype costs, pre-crash conditions are instead reproduced using critical near-collision road tests or crash tests with foam dummy vehicles [Sala, 2003]. However, these tests are often characterized by trial and error, not reproducible, and difficult to analyze, thus time-consuming and costly. Simulations are an alternative, but currently lack the possibilities for testing the complete system with full integration of the operating conditions, high level sensor characteristics, vehicle dynamics and complex traffic scenarios.

An efficient methodology and new tools are therefore required for evaluation of the performance and reliability of a PCS. This paper presents a series of evaluation tests of a PCS using the VEhicle-Hardware-In-the-Loop (VEHIL) test facility. This laboratory allows for testing of advanced driver assistance systems in a hardware-in-the-loop environment, where only the relative motion between host and target vehicle is reproduced.

The paper starts with a description of the PCS. Next, results of an accident study are provided. This study was performed to define test scenarios for the evaluation of the system. After a short introduction into the VEHIL facility the test set-up for the PCS is presented. The added value of VEHIL in the development process of the PCS is illustrated with test results. In addition, the PCS is modeled with the PRESCAN simulation tool to evaluate the PCS in a virtual environment. Finally, conclusions are presented.

PRE-CRASH SYSTEM

The prototype system used during the evaluation process was representative of first-generation pre-crash systems that have recently been offered as optional content on series production vehicles. Such systems typically utilize the pre-existing long-range, forward-looking radar (FLR) or laser sensors that are installed for adaptive cruise control or distance-keeping driver convenience systems to provide additional safety functions. The particular FLR used for this testing was the most-recent version of a product that Delphi has had in production since 1999. Some relevant performance specifications are noted in Table 1 below, along with an accompanying picture in Figure 3.

Table 1.
Forward-looking radar spec

Parameter	ACC-2 Specification
Range Coverage	1 – 150 m (for 10m^2 RCS)
Range Resolution	2 m (80 cm range bin)
Range Accuracy	2 m
Range Rate Coverage	-230 to +115 km/h
Range Rate Accuracy	± 1.8 km/h
Azimuth Coverage	15°
Azimuth Accuracy	±0.3°
Track Outputs	no classification; angular extent available
Tracking Data	15 targets
Acquisition Time	< 0.3 s
Cycle Time	100 ms
Sensor Size	(140 x 70 x 100) mm
Frequency	76 GHz

Figure 3. FLR module.

The prototype sensing system consists of a long-range radar with embedded pre-crash threat assessment algorithms working in conjunction with a laptop computer. As the radar detects and tracks objects within its zone-of-coverage, real-time target data is transmitted over the CAN bus to the laptop for data collection and display purposes. The CAN bus is also used to transmit the output decisions for driver warning and actuation commands for the motorized seat belt retractors and autonomous braking functions. A picture of the system configuration is shown in Figure 4.

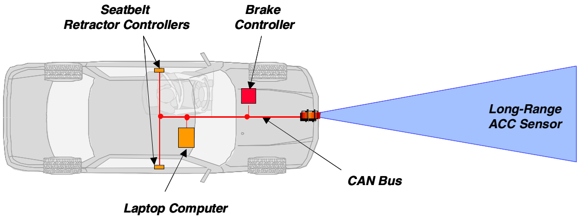

Figure 4. Pre-crash prototype system configuration.

The FLR within the PCS is responsible for converting real-world objects in front of the vehicle into radar targets and tracking those targets over time, including the range, range rate, azimuth angle, and other target attributes. The threat assessment algorithms must determine the threat level posed by each object and decide if and when a collision is imminent. For the purposes of this study, a triggering time for the motorized seat belt retractors was chosen to be at 500 ms before impact under all true collision scenarios. Of course, driver warnings are given significantly earlier than that. However, autonomously triggering seat belt countermeasures or brakes prior to that time increases the opportunities for false triggering in the event that the driver of either the host or target vehicle, or both, could evasively steers to avoid the impact. These tradeoffs in algorithm performance are typically different for each vehicle manufacturer based on their customer preferences. This conversion of real-world scenes to pre-crash threat assessment is depicted in Figure 5.

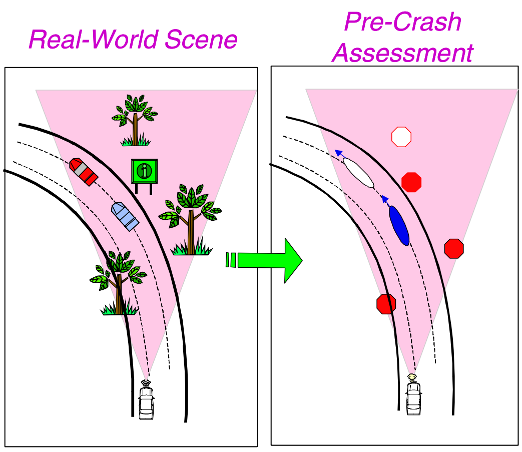

Figure 5. Pre-crash scenario assessment.

ACCIDENT STUDIES AND DEFINITION OF TEST SCENARIOS

The definition of the VEHIL test matrix started with an assessment of the field relevance of accident scenarios.

The field data were obtained from the 2000 General Estimates System (GES). Data for the GES comes from a nationally representative sample of US police reported motor vehicle crashes of all types, from minor to fatal.

Each year, 6.4 millions accidents take place on US roads. For this first evaluation in VEHIL only accidents involving two vehicles were analyzed. Those comprise of rear-ends, avoidance maneuver with roadway departure, opposite direction collisions, sideswipe collisions and intersecting path accidents. Figure 6 shows these accident scenarios found in the GES database.

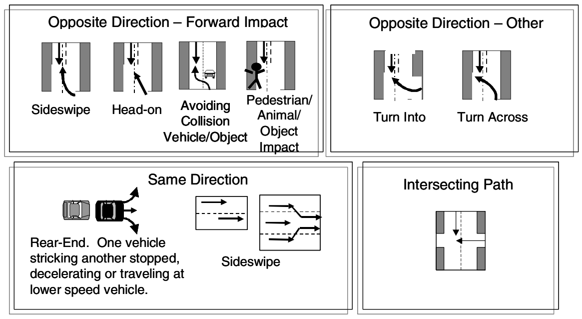

Figure 6. Relevant accident scenarios for PCS.

Rear-end: Of the 6.4 millions accidents, 1,710,639 were rear-ends, accounting for 27% of all accidents. Of those, (a) 1,370,239 accidents occurred when 2 vehicles are traveling in the same lane, where the critical event consisted of the front vehicle was traveling at a lower speed, and (b) 128,049 accidents occurred when 2 vehicles are traveling in the same direction but where one vehicle encroached into the other lane. These number exclude loss of control, vehicle failure, and accidents where an animal/object or pedestrian were avoided and resulted in a rear-end collision.

Avoidance maneuver: In the data, there were 1,454,581 accidents that occurred off roadway. Of those, 354,053 were due to avoidance maneuver or hitting a parked vehicle.

Sideswipe: 9% or 570,123 accidents resulted due to side-swipe collisions. Of those, 30,315 accidents occurred when 2 vehicles are traveling in the same lane, where the critical event consisted of the front vehicle was traveling at a lower speed.

Opposite Direction: There were 142,678 accidents that took place where 2 vehicles were traveling in opposing direction. Accidents that involved vehicle failure or loss of control were excluded.

Intersecting Paths: There were 1,575,413 accidents that involved 2 vehicles that were proceeding straight ahead and as a result, collided with each other.

As indicated the accidents were selected based on the relevancy of a first evaluation using VEHIL that included two vehicle accidents only. The selected accidents accounted for about 60% of all accidents.

INTRODUCTION TO VEHIL

The VEhicle Hardware-In-the-Loop (VEHIL) concept makes it possible to conduct experiments with full-scale intelligent vehicles in a laboratory, where only the *relative* motions between the test vehicle and obstacles are reproduced. This indoor test facility eliminates weather influences and provides a relative world that reduces the necessary space and vehicle speed considerably, resulting in a safe and adaptable testing environment. Testing with a full-scale vehicle, possibly treated as a 'black box', allows the possibility to test the real behavior of a complete system, with real phenomena such as noise and faults in the sensor data.

The Vehicle Under Test (VUT) is mounted on a chassis dynamometer and placed in an emulated environment consisting of mobile robots. Each robot, a so-called 'moving base' (MB), see Figure 7, emulates the motion of a specific road user relative to the VUT [Ploeg, 2002]. On the basis of real vehicle data of the VUT (measured by the chassis dynamometer since the vehicle itself is treated as a 'black box'), the Multi-Agent Real-time Simulator (MARS) calculates the relative motions and sends position commands to the MBs. In this way, the MBs adapt their positions according to the traffic scenario.

The VUT that is equipped with environment sensors will track the MBs as it would do with real road users when driving on a road. The pre-crash controller might activate safety actions such as active braking, and in an actual traffic situation the vehicle would decelerate. In the VEHIL facility, the corresponding braking forces are measured by the chassis dynamometer and converted into a predicted path of the intelligent vehicle. The MARS calculates the corresponding relative positions and the MBs adjust their relative positions accordingly. Figure 8 gives an overview of the working principle. The absolute equivalent of the emulated relative scenario can also be visualized on a computer. VEHIL is located in Helmond, the Netherlands, and is operational since November 2003 as an independent test facility.

TESTING A PRE-CRASH SYSTEM IN VEHIL

Experimental set-up

To overcome the difficulties of testing a PCS on a test track, VEHIL can provide an alternative approach. During the experiment the MB follows a crash trajectory, such that it is recognized by the sensor as a potential obstacle. When the controller estimates that a collision is imminent and unavoidable (taking conventional vehicle dynamics into account), it activates safety measures. However, an actual collision is avoided, because the MB can achieve a much higher lateral acceleration than a normal passenger car. It can therefore make an evasive maneuver at the last moment, while still triggering activation of the PCS, as illustrated in Figure 9.

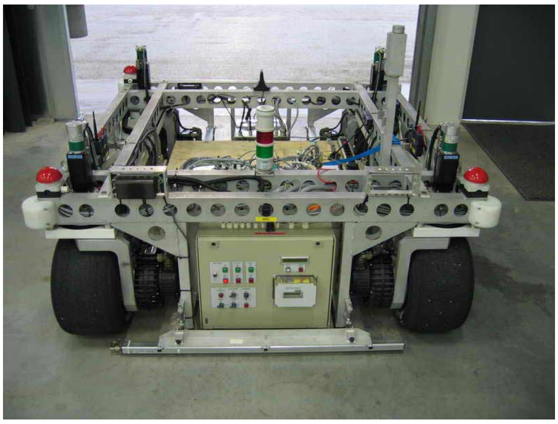

Figure 7. Moving Base.

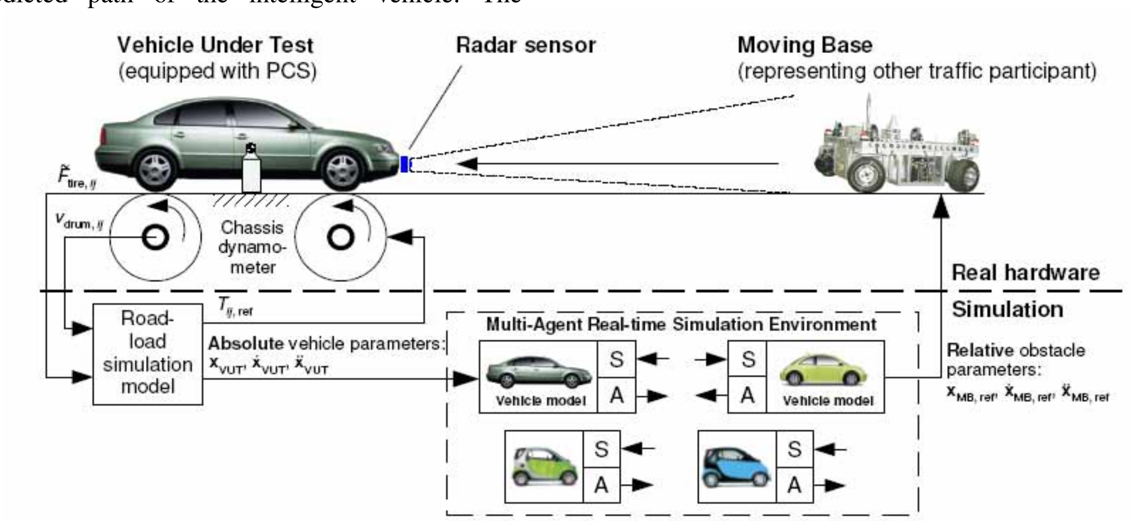

Figure 8. Working principle of VEHIL [Gietelink, 2004].

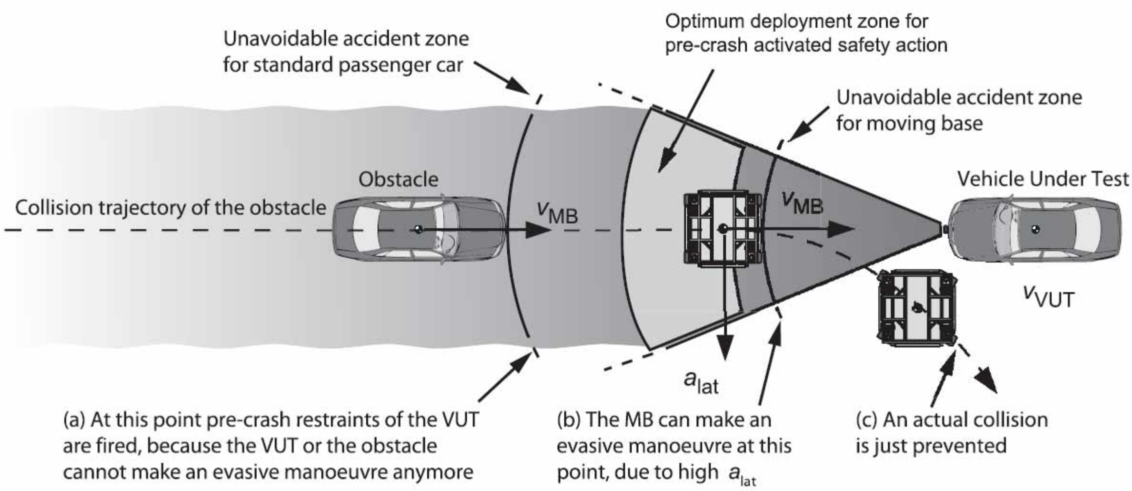

Figure 9. Pre-crash test for a head-on collision scenario in VEHIL.

These safety-critical experiments can be performed with relative speeds up to 50 km/h and closing distances up to 50 cm. At 50 km/h the lateral acceleration of 13 m/s^2 allows the MB to approach the VUT up to a time-to-collision of 120 ms without causing a real collision. In this way, it is possible to evaluate a PCS in a realistic, but non-destructive way. These VEHIL experiments are always performed open loop, since the test is finished at the moment the test vehicle responds, and there is no effect of vehicle actions on the relative motion.

The PCS obtains pre-crash information with a radar sensor. The vehicle is equipped with a reversible belt pre-tensioner that is tested with both a crash dummy and a human driver, as shown in Figure 10. Two different positions were evaluated:

- Leaning forward about 15° (Position-1) with and without 100 mm slack in the shoulder belt.
- Leaning forward about 30° (Position-2) with and without 100 mm slack in the shoulder belt.

The experimental setup for the scenarios as identified in the accident study (see Figure 6) basically consists of three different test types, illustrated in Figure 12 on the next page:

(a) The target vehicle (the MB) drives towards the host vehicle equipped with the sensor (the VUT).

(b) The target vehicle (the MB) is equipped with the sensor and drives towards the host vehicle (the VUT).

(c) One MB is equipped with the sensor and drives towards another MB. Both MBs can drive at a velocity of up to 50 km/h, ensuring a closing velocity of 100 km/h. During these scenarios the sensor is mounted on the Moving Base, as shown in Figure 11.

For each scenario different permutations of the scenario parameters were used to test the system exhaustively. Head-on collisions with full or partial overlap, near-misses or complete misses were simulated at different speeds. Also the approach was varied: pure longitudinal, under an angle or on a curve.

Figure 10. Experimental set-up of a pre-crash test.

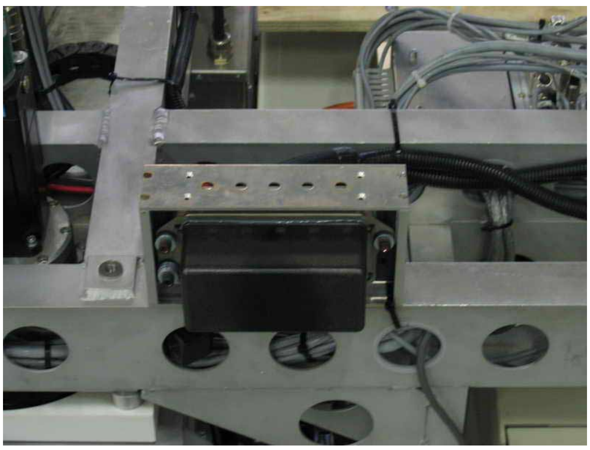

Figure 11. Sensor mounted on the Moving Base.

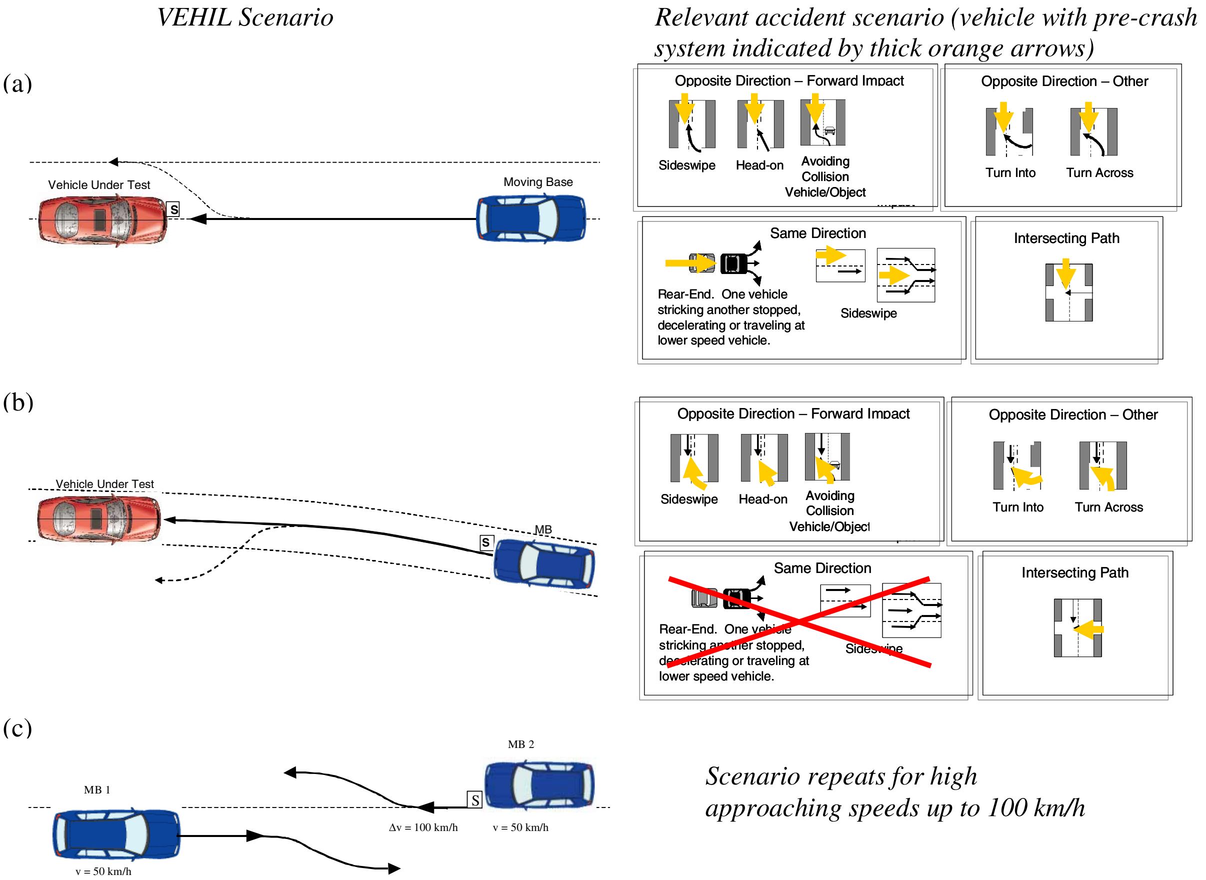

Figure 12. Pre-crash scenarios considered in the VEHIL tests: (a) target vehicle approaches host vehicle; (b) host vehicle approaches target vehicle; (c) two moving bases (one host and one target vehicle) drive towards each other up to a collision velocity of 100 km/h. Related accident scenarios indicated in right column.

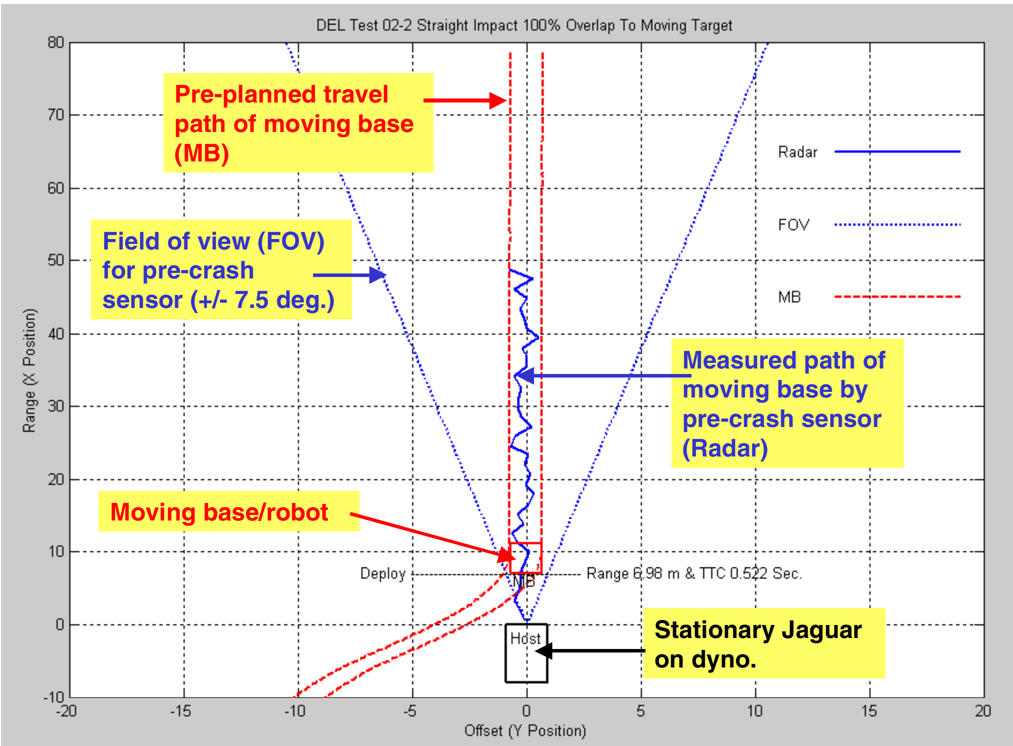

Figure 13. Test result rear-end scenario.

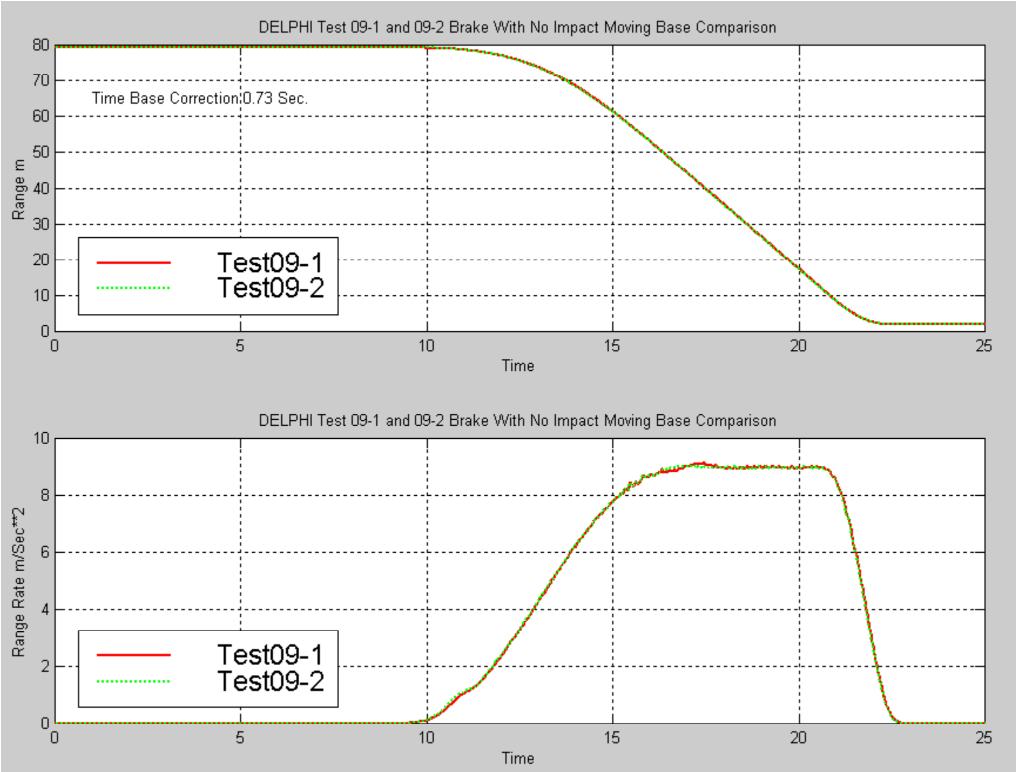

Figure 14. Comparison of test repeats.

Analysis of test results

In total 74 pre-crash tests were executed. Figure 13 shows the test results for a rear-end collision scenario at a relative speed of 50 km/h. During the tests it was verified that with a time-to-collision threshold at 500 ms the driver can be fully retracted from its forward position to an optimal crash position. This was true for both 15 and the 30 degrees position. Here it has to be noted though that the occupants do not undergo any deceleration due to braking. This may increase the required time for full retraction. Other test results indicated that a pre-crash brake assist function applied 1 s before the collision, a reduction in crash velocity of at least 5 m/s can be reached. This velocity reduction corresponds to a 40% reduction in the kinetic energy that has to be dissipated during this particular crash scenario. The PCS can therefore obtain a significant reduction in injury values [Lemmen, 2004].

Figure 14 shows results of a repeated test. It can be seen that scenarios are reproduced very accurately. The MB has a very high positioning accuracy of 10 cm. The maximum position error between two repeats is 3 cm. This enables to evaluate the effects of parameter tuning in between test runs. The repeatability and accuracy of the test setup made sensor validation and control system testing much easier and more flexible. It appeared to be useful for fine-tuning sensor post-processing algorithms, path prediction algorithms, and activation times. This was especially true for the tests that included severe braking. When performed with drivers, these tests are lacking accuracy and are difficult to repeat. For such conditions it is difficult to separate sensor noise introduced by the braking action from inaccuracy in the measurements. The detailed VEHIL measurements allowed to identify the sensor noise. This information is used to update the sensor algorithms, resulting in an improved performance under severe braking conditions.

Because of the high accuracy, repeatability and fast response, ground truth data can be compared very well to test results, in order to easily evaluate timing and sensor issues. An example of comparison of the radar and laser sensor data with the real 'ground truth' data is shown in Figures 15a and 15b, respectively. From this follows that the radar has a good performance with a dynamic accuracy of around 1.5 m. The dynamic accuracy of the range rate measurement is around 1 m/s. The range (rate) measurement is more accurate for scenarios with lower dynamic maneuvers. The laser system (not used for the PCS algorithm but available in the vehicle for testing) has slightly worse dynamic performance.

After fine tuning of the system it appeared that the system passed all tests, activating the belt system only when required and well in time. For further evaluation of the system drive tests are needed to check the performance under real world conditions.

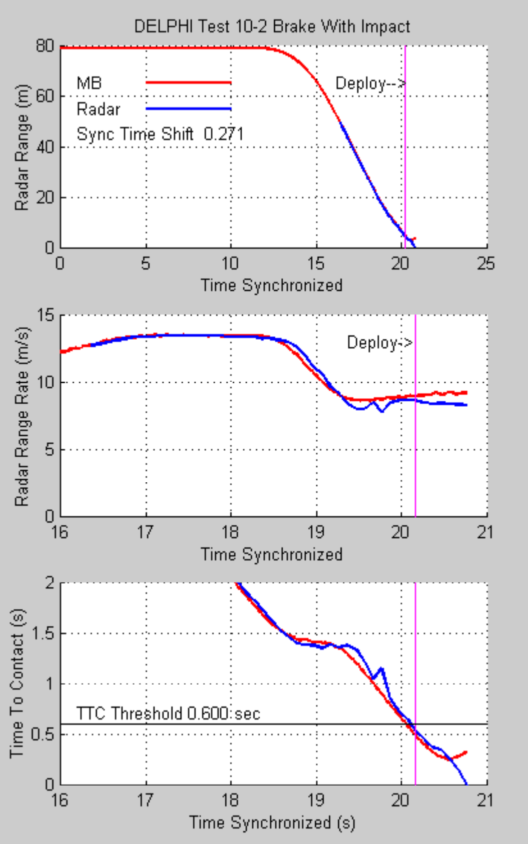

Figure 15a. Comparison of radar data to 'ground truth' data.

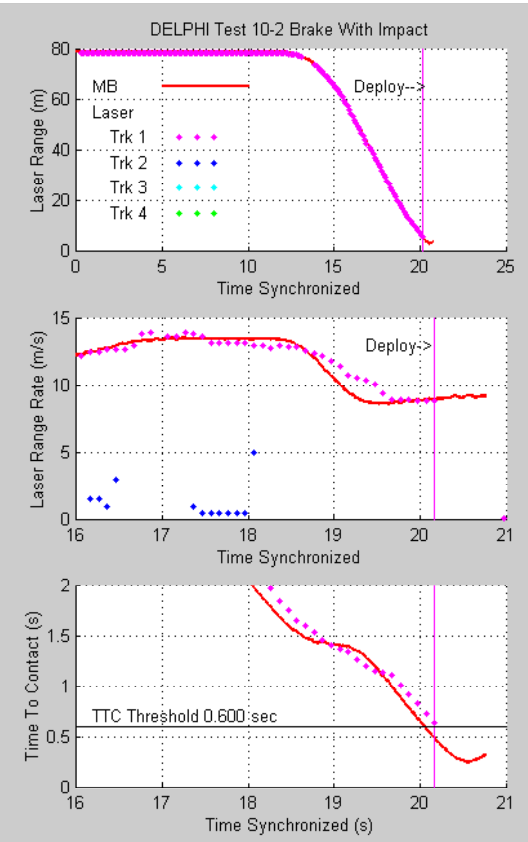

Figure 15b. Comparison of laser data to 'ground truth' data.

NUMERICAL SIMULATIONS

In addition to the VEHIL tests a numerical simulation model of the PCS is being developed to perform further system analysis. The model is developed in the PRESCAN (PRE-crash SCenario ANalyzer). In PRESCAN real world scenarios can be modeled in a virtual environment to simulate environment sensors. Figure 16 gives an example for a laser scanner. The simulated sensor output can be used for development and evaluation of the system, i.e.:

- assessment of different sensor types;
- assessment of sensor positioning;
- prototyping of sensor post-processing algorithms;
- prototyping of data fusion algorithms;
- prototyping of control/decision algorithms; and
- definition of the overall system architecture.

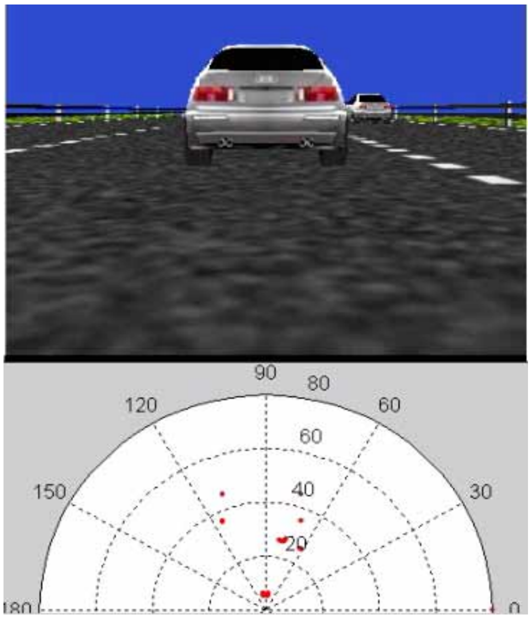

Figure 16. Laser scanner model: view from sensor position and sensor output.

Simulation models are constructed from a library set that contains scenarios, sensor models, infrastructural elements, relevant obstacles and vehicle models. The sensor library currently provides models for FMCW radars [Thean, 2004], stereo camera [Sunyoto, 2004] and laser. Models of different detail and complexity are provided for different phases of the design process. On a first level, basic functional models are provided that give deterministic information on the position, velocity, and shape of objects. These models can be extended with effects that represent noise and errors in a basic way. The specific effects that deteriorate the sensor performance can be obtained from VEHIL tests. Finally, dedicated physical sensor models are provided for detailed simulations. These physical models are hardware specific.

For the radar model targets are modeled using a small plate approximation, meaning that the object is divided into sub-regions that each has a specific radar cross section. Each sub-region is dealt with as a single flat plate with a given orientation. The radar model calculates the vector sum of the reflected waves from all objects in the field of view. The summation keeps track of signal phases. As a result interference effects are accounted for.

The PCS considered in this study uses mechanically scanned frequency modulated radar. This device was modeled in PRESCAN. To this end the existing radar model [Thean, 2004] was adjusted to emulate the hardware radar and sensor data processing algorithms were implemented. Amongst others these included algorithms for amplitude weight and IQ balance, Fast Fourier Transformation, detection thresholding and range-rate determination.

Figure 17 provides a simulation result of the reflection of the moving base. The intensity of reflected signals is plotted for the different beams of the radar as function of the range. In this first simulation a single radar cross section was assigned to the moving base. Variations in intensity of the MB occur due to the fact that adjacent beams are in a different phase of the frequency modulation.

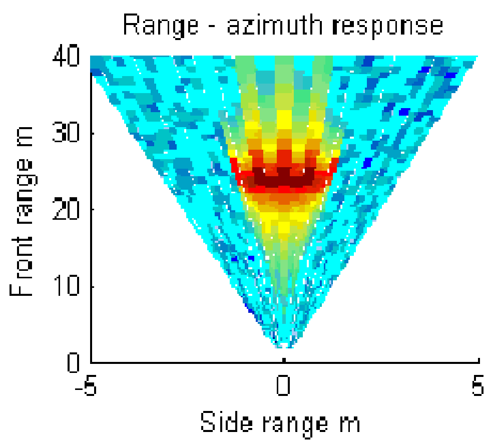

Figure 17. Radar sensor model: view from sensor position and sensor output.

The simulated radar output is processed using the implemented data processing algorithms. Figure 18 compares the resulting range estimations for a given test scenario with the actual VEHIL data. Note that experimental data are available only for ranges below 50 m. It can be seen that simulated data correlate quite well with experimental data. Although this high level validation provides confidence in the model, further work is needed to develop a more detailed radar model of the moving base. Once such a model is available a wide range of scenarios can be evaluated using PRESCAN to further fine tune the system and consider real world conditions.

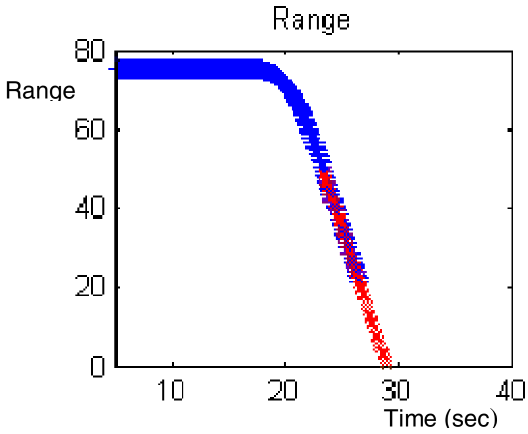

Figure 18. Comparison of simulated (blue) and real range (red) of MB.

CONCLUSIONS

An evaluation of a pre-crash system (PCS) using the VEhicle Hardware-In-the-Loop (VEHIL) test facility was presented. The prototype PCS uses a long-range forward-looking radar sensor installed for adaptive cruise control. To provide additional safety functions the sensor is linked to motorized belt retractors in the front seats. For this study the trigger time of the seat belt retractors was chosen to be at 500 ms.

A total set of 74 pre-crash scenarios was run in VEHIL, representing rear-end impacts, avoidance maneuvers with roadway departure, opposite direction collisions, sideswipe collisions and intersecting path accidents. The test scenarios were based on field data obtained from the 2000 General Estimation System (GES). The considered scenarios accounted for about 60% of all accidents in the GES.

The repeatability and accuracy of the VEHIL test setup allowed for fine-tuning of the sensor post-processing algorithms, path prediction algorithms, and activation times. This was especially true for the tests that included severe braking where accurate measurements are required to identify sensor noise due to braking.

After fine tuning of the system it appeared that the system passed all tests, activating the belt system only when required and well in time.

For further evaluation of the system drive tests are needed to check the performance in real world conditions. These activities can be supported using a detailed simulation model of the radar sensor that is currently under development. The model is based on VEHIL test data.

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