Pre-crash Test Capabilities at VeHIL

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Abstract**-- In the last few years, the developments in the field of ADA systems shifted from comfort oriented systems to safety oriented systems. Consequently, the complexity of the systems, and thus the complexity of testing those systems, increased. This leads to a demand for reproducible, efficient and safe testing methods for ADA systems in general, and pre-crash systems in particular. A new method for evaluation of pre-crash systems is presented, consisting of TNO's Vehicle Hardware-in-the-Loop facility (VeHIL) and TNO's Crash Lab. This method, called VeHIL/Pre-crash, aims to support the development and verification of pre-crash systems, increasing the level of reproducibility, effectiveness and safety of the testing process. To this end, a test vehicle, positioned on a roller bench, is placed in a simulated traffic environment. In order to provide the test vehicle's environment sensor input, one of the simulated traffic participants is represented by a rail guided target vehicle, which is stopped by crumple tubes.**

Index terms**—Pre-crash systems, VeHIL, Advanced Driver Assistance Systems, testing/evaluation**

I. INTRODUCTION

Advanced Driver Assistance (ADA) systems are increasingly becoming available in passenger vehicles. In general, this type of systems comprises one or more environment sensors such as radar, camera or lidar and a control algorithm that informs the driver or even autonomously influences the vehicle by means of the throttle and/or brakes. Examples of ADA systems are Adaptive Cruise Control (ACC), aiming to keep a set headway with respect to the forward vehicle and Forward Collision Warning (FCW), which warns the driver in case of a possible collision. The first developments in the field of ADA primarily aimed to increase driver comfort, starting with cruise control and now resulting in ACC. In the last few years however, ADA research is directed towards increasing the safety of the driver and the passengers. Current research concentrates on collision warning, collision mitigation and even collision avoidance [1], [2].

The above development indicates a shift towards ADA systems that operate under critical traffic conditions, especially resulting in so-called Pre-Crash Sensing (PCS) systems. As a consequence, the system complexity increases and at the same time dependability aspects such as reliability and availability are becoming much more important. The importance and complexity of experimental tests therefore increases significantly. Inherently to the nature of the system to be tested, testing conditions are also becoming more critical with respect to safety of man and material. These requirements lead to a demand for reproducible, efficient and safe testing methods for ADA and pre-crash systems.

A short study on the state of art of evaluating PCS systems – characterized by the fact that they aim to mitigate the effects of an unavoidable collision – revealed several activities:

- CAMP, the research plan for 2005–2008 of the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation. Its target is to develop objective test procedures and obtain safety benefits estimates of pre-crash sensing systems.
  Examples of such systems are airbag pre-arming, seat belt pre-tensioning, and emergency brake assist.
- World-wide research and development in PCS systems such as seat belt pre-tensioning, emergency brake assist, seat adjustment and pedestrian protection by OEM's and suppliers (e.g. Toyota, Mercedes, Ford, Honda, Nissan, BMW, Autoliv, Conti Teves, Delphi and TRL)
- EU research projects such as:
  - ASTE (SP, Feasibility study for setting up a performance testing program for ICT based safety systems for road transport, 2006–2007)
  - Aprosys (TNO, Advanced protection systems to improve passive safety, FP6)
  - PReVENT (DaimlerChrysler, contribute to road safety by developing and demonstrating preventive safety applications and technologies, FP6)
  - PReVAL (subproject, evaluation framework for impact assessment of preventive safety applications, FP6)

– Beyond NCAP, EuroNCAP's approach to verification of active safety systems.

State-of-art PCS test methods include real crashes in a crash facility using an IIHS barrier and basic proving ground testing with collision objects such as balloon vehicles (standing still or mounted on moving vehicles) and foam objects.

At TNO a facility was developed, called VeHIL, which supports the development process of ADA and pre-crash systems [3]. VeHIL is positioned in the V-shaped development methodology as commonly used by OEM's and 1st tier suppliers (Figure 1).

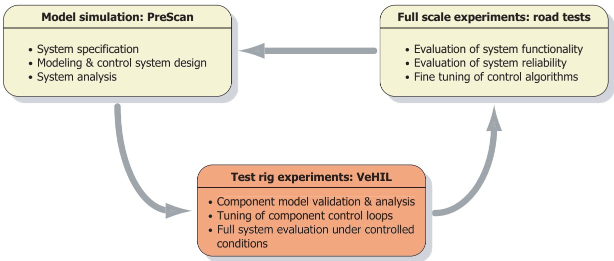

Figure 1 – V-shaped development methodology

VeHIL is aiming at an increased level of *reproducibility*, allowing for a fast iteration in algorithm optimization, *effectiveness* by targeting the problem, *safety* by testing safely for man and material and *efficiency* by a high test throughput.

II. VeHIL Principle

VeHIL constitutes a traffic simulation, in which one vehicle is the real test vehicle (Vehicle Under Test – VUT) and the motions of selected other simulated vehicles are represented by wheeled mobile robots so as to provide environment sensor input for the VUT. The key principle of VeHIL is that only relative motions of traffic participants with respect to the VUT are considered. In other words: the position, velocity and acceleration of neighboring vehicles are expressed in terms of the local VUT co-ordinate system. As a consequence, the entire traffic system is transformed to a lower velocity region, loosely formulated. This principle is illustrated in Figure 2.

The left side of this figure depicts an overtaking maneuver; the upper vehicle is the VUT and the lower one the overtaking vehicle. Their velocity vectors are shown as well.

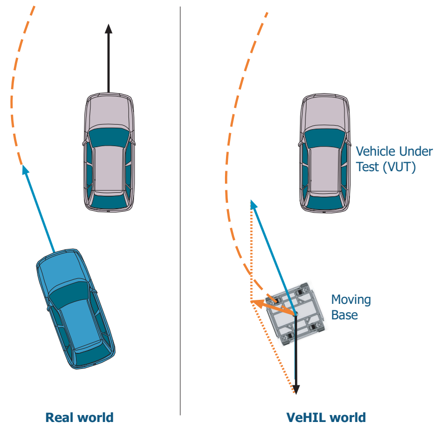

Figure 2 – Relative motion in VeHIL

Expressing the velocity vectors in the VUT co-ordinate frame results in the VUT standing still (with respect to its own co-ordinate frame) as shown on the right side. The resulting velocity vector of the other vehicle indicates a crabwise movement at relatively low velocity. Obviously, this crabwise movement cannot be driven by a common vehicle, which is why wheeled mobile robots are used to represent other road users.

A. Mars

The core component of VeHIL is a real-time simulation program called 'Multi Agent Real-time Simulator' (MARS) [4]. Using MARS, a specific traffic maneuver can be programmed and disturbances can be injected. In the MARS framework, the traffic participants are called *entities*, denoted by E. The dynamic behavior of each entity E_i is described by a simulation model e.g. developed in MATLAB/Simulink. Each entity E_i is represented as an *object* O_i with certain attributes in the *virtual world*, which is a formal representation of the environment relevant to the entity. Objects are static components: they cannot change their attributes themselves, but entities can operate on them. The link between an entity E_i and an object O_i is established by means of a 'sensor' S_i and an 'actuator' A_i. Note that S_i and A_i are not real sensors and actuators but merely a means of communication between objects and their corresponding entity model describing the object's dynamic behavior. Figure 3 shows a schematic picture of MARS.

The interaction between objects is dynamical, in the sense that it depends on the specific situation. In a car following situation for instance, the VUT with ACC only interacts with the directly preceding vehicle and not with other vehicles. This situation dependent interaction is a key property of MARS. The dynamic behavior of one specific entity, in this case E_1 as shown in Figure 3, is not described by a model, but generated by the real VUT via a real-time communication link between the VUT and the corresponding object O_1 in MARS. This 'places' the VUT in the virtual world that represents a traffic maneuver or situation.

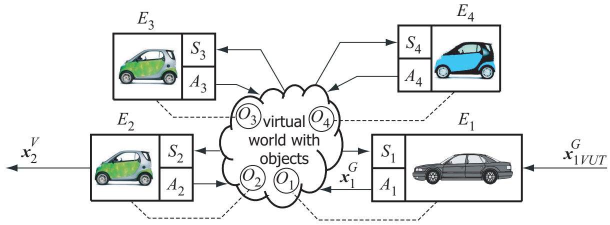

Figure 3 – Schematic representation of MARS

Within MARS, each object i has a state vector $\boldsymbol{x}_i^G$ containing the vehicle's position, velocity and acceleration with respect to a global co-ordinate frame $\{G\}$. During simulation, a co-ordinate transformation is performed to express the state vector of each object i in terms of the VUT co-ordinate frame $\{V\}$. The resulting relative motion vector $\mathbf{x}_i^V$ can then be sent to a wheeled mobile robot as a desired position/velocity/acceleration. As a result, the motion of the wheeled robot, called a *Moving Base*, with respect to the VUT corresponds to the relative motion of both vehicles in reality. In this way, the Moving Base provides realistic sensor input for the VUT's environment sensors.

B. Moving Bases

The high performance wheeled mobile robots, called Moving Bases (MBs), are very maneuverable and capable of achieving high acceleration and deceleration (up to 10 m/s^2) to be capable of performing the maneuvers necessary in VeHIL. An essential property of the MB is its ability to provide ground truth data as its position is accurately known (+/- 0.02 m) using a grid of magnets mounted in the VeHIL floor.

C. Roller bench

Although the VUT is effectively standing still during the experiment, it should still be placed on a roller bench that simulates the inertia and the road load of the VUT. The VUT therefore really drives, which is necessary for many ADA systems to operate correctly.

D. Full set-up

The full VeHIL set-up is shown in Figure 4. This figure illustrates the relation between the various components as described above.

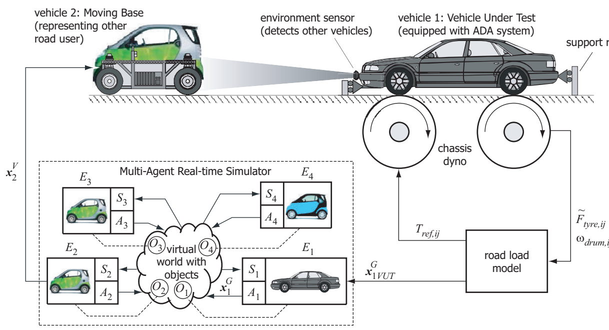

Figure 4 – Full VeHIL set-up

This figure clearly shows that VeHIL is a *closed-loop* system: all VUT actions will result in adaptation of the relative motion between the simulated traffic participants which in turn results in a certain MB motion. This motion is sensed by the VUT's environment sensor which will trigger the ADA system to react and change the VUT motion.

III. A NEW PRE-CRASH SYSTEMS TEST METHOD

Testing VeHIL focuses on effectiveness, reproducibility and safety for ADA systems in general, but the effectiveness for PCS systems, where a minimum Time-To-Collision (TTC) is necessary, is not optimal. The target for PCS testing yields speeds up to 120 km/s and minimum TTC close to 0. As VeHIL 'only' allows for minimum 500 ms TTC, the possibilities to test 'hit' scenario's for collision mitigation systems are limited. This limitation is inherently caused by the application of wheeled mobile autonomous robots, which have a limited maximum deceleration.

A new test set-up, called VeHIL/Pre-crash (patent pending) is being developed. The method consists of a rail guided target vehicle which is stopped by crumple tubes. This set-up achieves a minimum required TTC of 100 ms (and preferably 50 ms). The set-up can be implemented by extending the VeHIL facility with rail guidance or by combining TNO's crash lab and the VeHIL facility, which are now at the same location.

A pilot VeHIL/Pre-crash test was conducted for the pre-crash side impact protection system developed in the European FP6 project APROSYS. In the crash lab facility a moving base dummy was placed on a test sled, called the Pre-Crash Test Object (PCTO). The minimum TTC was approximately 50 ms, and the test results were compatible to VeHIL due to target similarity.

The target speed was fixed at 64 km/h (standard EuroNCAP crash test configuration) and the angle of approach was fixed and determined by the orientation of the vehicle under test with respect to the sled. Therefore, only simple hit and "straight path" traffic scenarios such as read-end collision, head-on collision and intersection collision can be tested. Furthermore, merely *open-loop* testing is possible, i.e. an action of the VUT such as braking, will not be reflected in the PCTO motion, as is the case in VeHIL (Figure 4).

A phased implementation plan is developed to include the VUT in the test in a closed-loop fashion and to enable evaluation of all possible traffic scenarios, such as cut-in and left/right turn, including collisions and near misses.

Implementation phase 0: Proof of principle

For proof of principle, the basic set-up is used, i.e. the Crash Lab and VeHIL components are not adapted. A preliminary test has been conducted for the implementation phase. The PCTO was mounted on the test sled in the Crash Lab, like in the pilot test, and the vehicle environmental sensor was placed at the end of the crumple tubes. The sensor was coupled to the VUT which was mounted on the roller bench of the VeHIL facility (Figure 5).

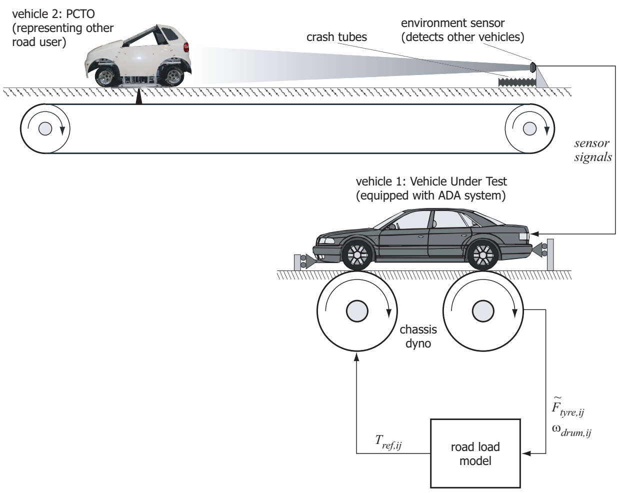

Figure 5 – VeHIL / Pre-crash implementation phase 0

With this set-up the action of the vehicle (e.g. by braking) is included. This results in a proof of concept for reproducible and safe full scale testing of pre-crash systems with a low TTC, allowing to obtain quantified and comparable figures with respect to system performance (e.g. measured reduction of impact velocity in case of a braking vehicle). The scenarios that can be evaluated are limited to open loop hit, straight-path scenarios with constant target speed. Near miss scenarios can be evaluated by introducing a lateral displacement to the sensor.

Implementation phase 1: Sensor mapping

In this stage, the speed and the position of the PCTO are no longer fixed, and the sensor is not coupled to the vehicle (Figure 6). This stage is relevant for 1st tiers suppliers, but for OEM's to a lesser extend, and results in reproducible and safe sensor mapping (benchmarking) with very low TTC for user-specified target velocity profiles. Benefits are again a black box performance evaluation and quantified and comparable figures with respect to sensor performance for a wide operating range with respect to target position, velocity and acceleration. Scenarios that can be evaluated are limited to open loop hit, straight-path scenarios with user-specified target speed. Again, near miss scenarios can be evaluated by lateral displacement of the sensor. Furthermore, this phase is open loop by definition.

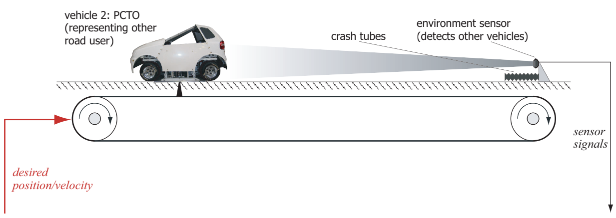

Figure 6 – VeHIL / Pre-crash implementation phase 1

Implementation phase 2: PCS testing

In the PCS testing phase, the previous phase is extended with the VUT being placed on the roller bench and coupled with the sensor in the Crash Lab (Figure 7). The system is still open-loop, as no coupling exists between the vehicle and the sled on which the PCTO is mounted. The result of this phase is reproducible and safe full scale testing of pre-crash systems down to TTC of 100 ms (or even lower) for user-specified target velocity profiles. Benefits of this method are (almost) black box performance evaluation and quantified and comparable figures for system performance such as measured impact speed, timing of belt pre-tensioning, etc. The scenarios that can be evaluated are limited to open loop near-miss and hit, straight-path scenarios with user-specified target speed.

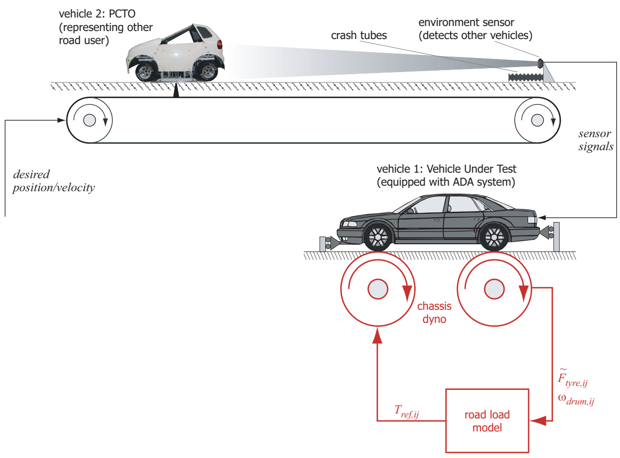

Figure 7 – VeHIL / Pre-crash implementation phase 2

Implementation phase 3: Traffic scenario extension

The variety of scenarios that can be evaluated is extended by mounting the PCTO and the environmental sensor on a rotating platform (Figure 8). This enables testing non-straight scenarios such as left/right turn, take-over etc.

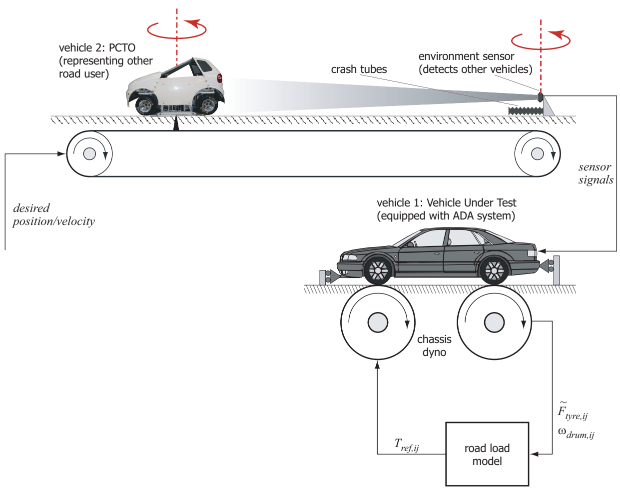

Figure 8 – VeHIL / Pre-crash implementation 3

Figure 9 shows the VeHIL principle used to calculate the relative motion of a target vehicle (represented by a Moving Base) with respect to a host vehicle (represented by the VUT on the roller bench). First the motion of target vehicle T with respect to host vehicle V (VUT) is described. Then the VUT co-ordinate frame $\{V\}$ is taken as new fixed VeHIL world.

Figure 10 shows the VeHIL/Pre-crash principle which is used to calculate the relative motion of a target vehicle (represented by the PCTO) with respect to a host vehicle (represented by a sensor in the Crash Lab and a vehicle on the roller bench in

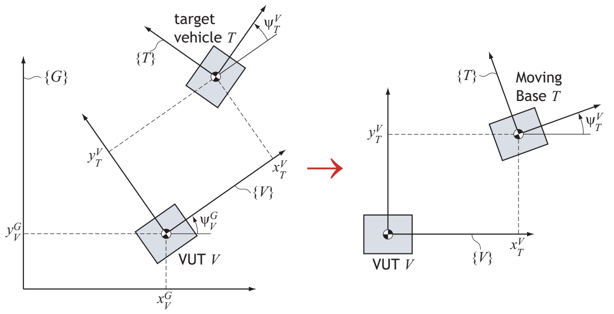

Figure 9 – VeHIL coordinate transformation

the VeHIL facility). First the co-ordinate frame $\{R\}$, directed from host vehicle V (VUT) towards target vehicle T is described. Then the motion of target T and host V with respect to $\{R\}$ is described. Finally $\{R\}$ is taken as new fixed VeHIL/Pre-crash world. Note that especially at near misses the rotational velocity of the sensor and the PCTO can become rather large, due to the co-ordinate transformation. The faster the target vehicle will pass the VUT, the faster the co-ordinate frame will rotate, or vice versa, the faster the sensor and the PCTO body will rotate.

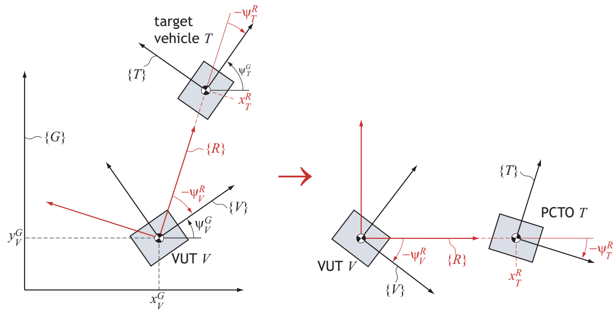

Figure 10 – VeHIL/Pre-crash coordinate transformation

Although Figure 10 suggests that the entire VUT will rotate, this is not practical as it would require rotating the entire roller bench in real-time. Therefore, the sensors are detached from the VUT and placed on a separate platform.

This phase results in reproducible and safe full scale testing of pre-crash systems down to TTC = 100 ms (or even lower) for user-specified target velocity profiles and a wide range of traffic scenarios.

Implementation phase 4: Collision avoidance (by braking)

Closed loop testing in which the VUT and the MB interact, is obtained by adding a traffic model in a real-time traffic simulator to the previous phase (Figure 11) resulting in reproducible and safe full scale testing of pre-crash and collision avoidance systems down to TTC = 100 ms (or even lower) for user-specified target velocity profiles and a wide range of traffic scenarios. Note that this final setup is very similar to the VeHIL set-up (Figure 4), resulting in comparable experiment results.

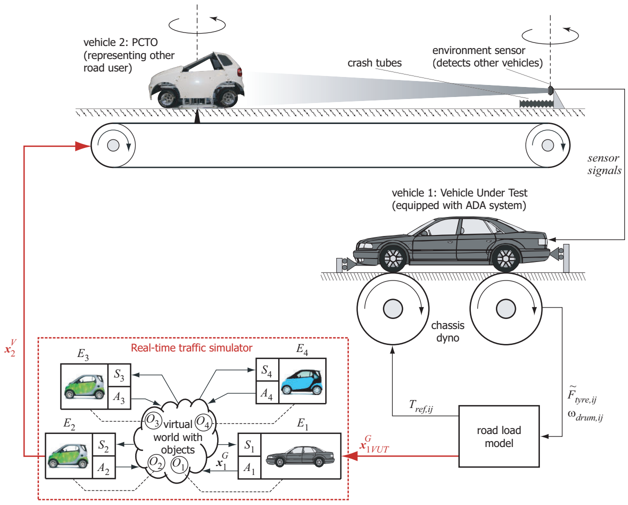

Figure 11 – VeHIL/Pre-crash implementation 4

Final Basic scenario's

At the moment, eleven 'scenario primitives' covering the majority of traffic maneuvers as revealed by various accident databases, are defined that can be tested in the PCS test set-up (Figure 12), being: rear-end collision, head-on collision, cut-in with negative and positive speed-difference, left turn (twice: host or target turning left), left turn opposite (twice: host and target swapped), intersection and roundabouts (twice: host and target swapped).

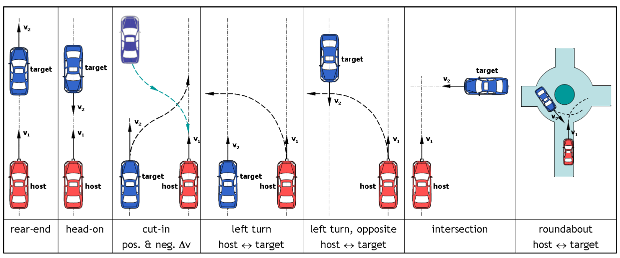

Figure 12 – Scenario primitives

IV. Conclusions

VeHIL/Pre-crash is a promising development for reproducible and safe testing with very low TTC (down to 50 ms) of vehicles equipped with safety ADA systems being pre-crash and even collision avoidance systems. In the future, any traffic maneuver is potentially possible. This method consumes little space because the target always moves along the same straight line, regardless of the type of maneuver. As a consequence, side impact testing is just as easy as frontal approaches. Furthermore, closed-loop as well as open-loop testing is possible in VeHIL/Pre-Crash in exactly the same manner as in VeHIL.

However, sensors have to be removed from host vehicle, compromising the 'black box' approach. Furthermore, testing with more than 1 target may be done by additionally using a Moving Base in VeHIL; the feasibility of this option however is yet unknown.

Also specifically for the rotation option (non-straight trajectories) there are some issues yet to be solved:

- Sensor detection is probably compromised by hall walls due to sensor platform rotation. This can be solved by covering the walls with absorbing material or paint.
- Sensor fusion is only realistic if sensors have the same relative position as in reality. This can cause centripetal forces that might become too high for some sensors.

V. References

[1] Vahidi, A., et al. Research Advances in Intelligent Collision Avoidance and Adaptive Cruise Control. *IEEE Transactions on Intelligent Transportation Systems*, 4(3):143–153, September 2003

[2] Bishop, R., *Intelligent Vehicle Technology and Trends*. Artech House, Norwood, MA, USA, 2005

[3] Gietelink, O.J., J. Ploeg, B. de Schutter and M. Verhaegen, *Development of Advanced Driver Assistance Systems with Vehicle Hardware-in-the-Loop Simulations*. Vehicle System Dynamics, Vol. 44, No. 7, July 2006, pp. 569–590

[4] Papp, Z., M. Dorrepaal and D.J. Verburg, Distributed Hardware-in-the-Loop Simulator for Autonomous Continuous Dynamical Systems with Spatially Constrained Interactions. In *Proceedings of the 11th IEEE/ACM International Workshop on Parallel and Distributed Real-Time Systems*. Nice, France, April 22–26, 2003