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VEHIL – HIL Testing of Advanced Driver Assistance Systems

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A new Hardware-in-the-Loop method for the design of Advanced Driver Assistance (ADA) systems for road vehicles is presented. This method, called VEHIL, aims to support the development and verification of ADA 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. A selection of simulated traffic participants is represented by wheeled mobile robots in order to provide the test vehicle's environment sensor input. VEHIL is positioned in the development methodology as commonly used by OEM's and 1st Tier suppliers and the added value of VEHIL is illustrated by means of three test cases regarding sensor mapping, ACC and collision mitigation.

1 Introduction and motivation

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 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 – 4].

The above development indicates a shift towards ADA systems that operate under critical traffic conditions. 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 magnitude 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. With these aspects in mind, a hardware-in-the-loop facility, capable of testing vehicles equipped with ADA systems, has been developed. This facility, called VEHIL, supports the development process of ADA systems, aiming at an increased level of:

- *reproducibility* – allowing for a fast iteration in algorithm optimization,
- *effectiveness* – targeting the problem,
- *safety* – testing safely for man and material,
- *efficiency* – high test throughput.

2 The VEHIL working 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 as firstly described in [5], is that only relative motions of traffic participants with respect to the VUT are considered. In other words: the position, velocity and acceleration of neighbouring 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 1.

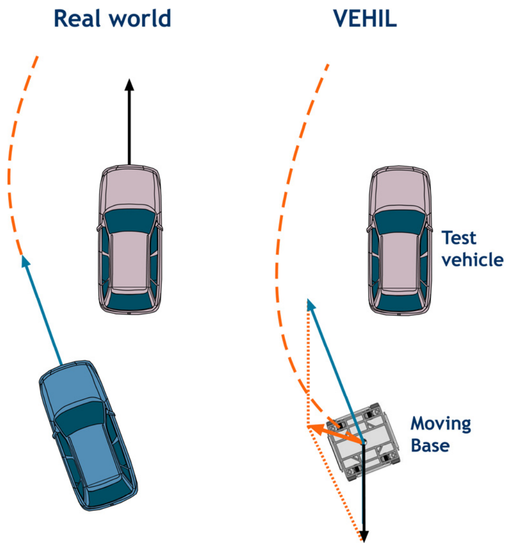

Figure 1 – Relative motion in VEHIL

The left side of this figure depicts an overtaking manoeuvre; the grey vehicle is the VUT and the blue one the overtaking vehicle. Their velocity vectors are shown as well. Expressing the velocity vectors in the VUT co-ordinate frame results in the VUT standing still (with respect to it's 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. This and other VEHIL components will be explained in the next section.

3 VEHIL components

3.1 MARS

The core component of VEHIL is a real-time simulation program called 'Multi Agent Real-time Simulator' (MARS) [6]. Using MARS, a specific traffic manoeuvre or situation can be programmed and disturbances can be injected. In the MARS framework, the traffic participants are called *entities*, denoted by E. The dynamic behaviour 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 behaviour. Figure 2 shows a schematic picture of MARS.

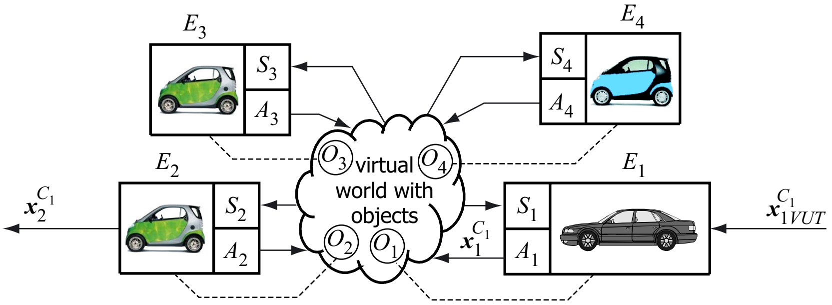

Figure 2 – Schematic representation of MARS

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 behaviour of one specific entity, in this case E_1 as shown in figure 2, 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 manoeuvre or situation.

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 $\{C_1\}$. The resulting relative motion vector $\boldsymbol{x}_i^{C_1}$ can then be send 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.

3.2 Moving Bases

A Moving Base (MB) is a high performance wheeled mobile robot, capable of performing the manoeuvres necessary in VEHIL. To this end, the MB is very manoeuvrable and capable of achieving a high acceleration and deceleration. Moreover, the response to acceleration and steering commands has a bandwidth which significantly exceeds that of normal road vehicles. As shown in figure 3, currently two moving bases are available, one without and one with body. The latter one is designed to be representative to common automotive environment sensors such as radar, lidar and vision systems.

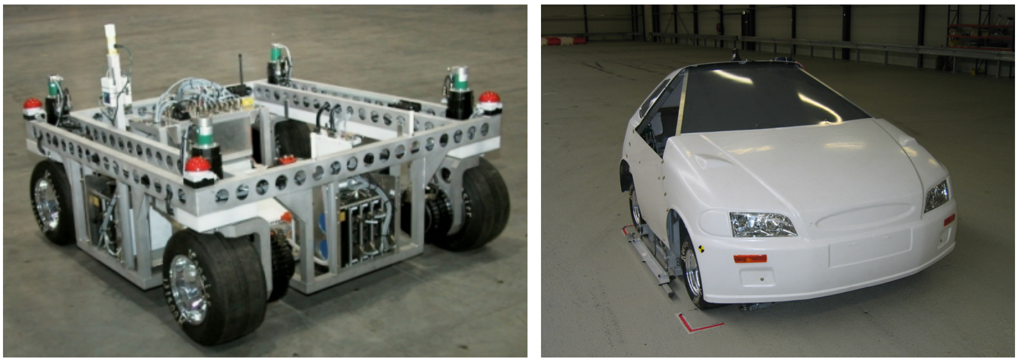

Figure 3 – Moving Base without body (left) and with body (right)

Table 1 shows a list of the main specifications. A more detailed overview of the Moving Base is given in [7].

Table 1 – Specifications of the Moving Bases

vehicle mass	560 kg
wheel base	1.4 m
track width	1.4 m
maximum velocity in all directions	50 km/hr
maximum acceleration	10 m/s^2
installed power	32 kW
acceleration from 0 to 50 km/hr	2.1 s
battery pack	NiMH D-cells

An essential property of the MB is that it's position is accurately known using a grid of magnets mounted in the VEHIL floor. The position accuracy is in the range of +/- 0.02 m. The MB position can therefore be considered as the 'real' position compared to the measurement of the environment sensor(s) of the VUT.

3.3 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. The VEHIL roller bench is a 4 wheel drive bench, allowing vehicles up to 3500 kg to decelerate with a maximum of 10 m/s^2, corresponding to (or even slightly exceeding) an emergency stop. Heavier vehicles up to 12000 kg can also be placed on the roller bench, albeit that the maximum deceleration then decreases.

3.4 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.

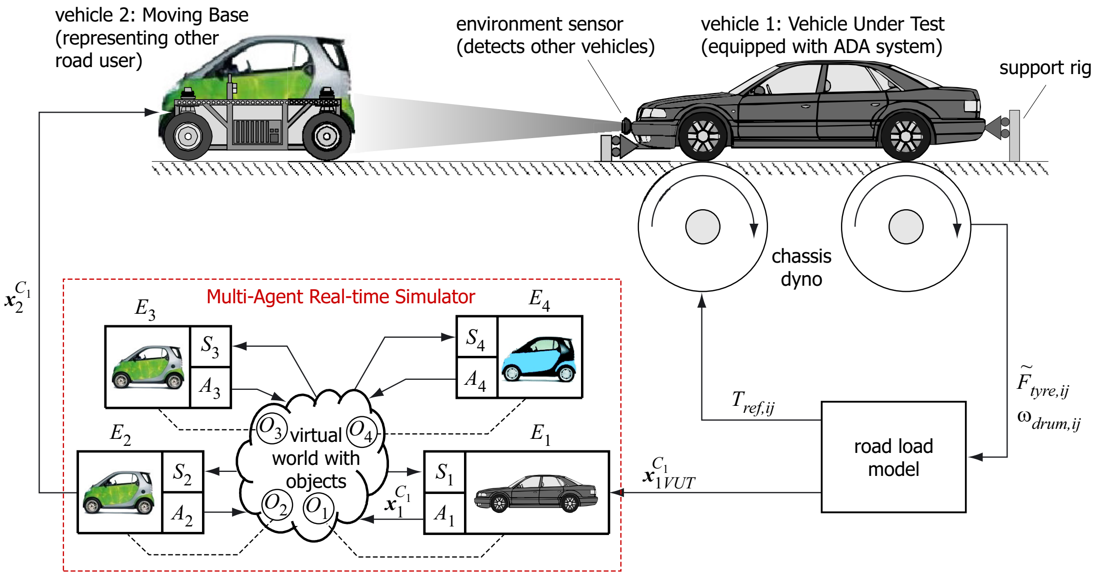

Figure 4 – Full VEHIL set-up

If we simplify the VEHIL set-up by taking a car following situation as an example, with the VUT being equipped with ACC and the directly preceding vehicle simulated, the block diagram of figure 5 is obtained.

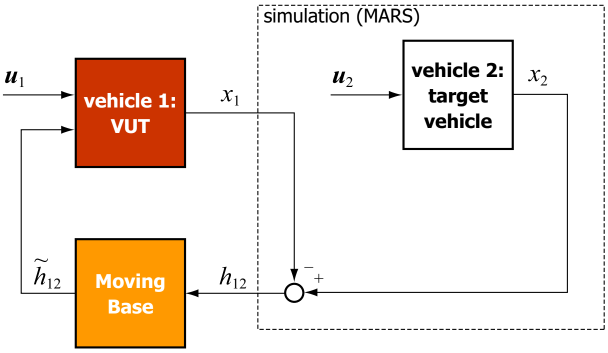

Figure 5 – Block diagram of a VEHIL car following situation

This figure clearly illustrates the hardware-in-the-loop character of VEHIL: the VUT is the hardware, whereas the simulated traffic environment is part of the loop which is closed through the MB. It also directly follows why the MB must have a high bandwidth: the simulated headway h_{12} and the distance $\tilde{h}_{12}$ between the VUT and the MB must be as close as possible, which can only sufficiently be established if the MB has a bandwidth significantly exceeding that or normal road vehicles.

The vectors $\boldsymbol{u}_1$ and $\boldsymbol{u}_2$ are inputs of the VUT and the simulated target vehicle respectively. $\boldsymbol{u}_1$ is used to test setpoint tracking behaviour, e.g. by changing the set velocity of the VUT and $\boldsymbol{u}_2$ is applied for assessment of disturbance behaviour.

4 Automotive development methodology

The development methodology as commonly used in the automotive industry is depicted in figure 6.

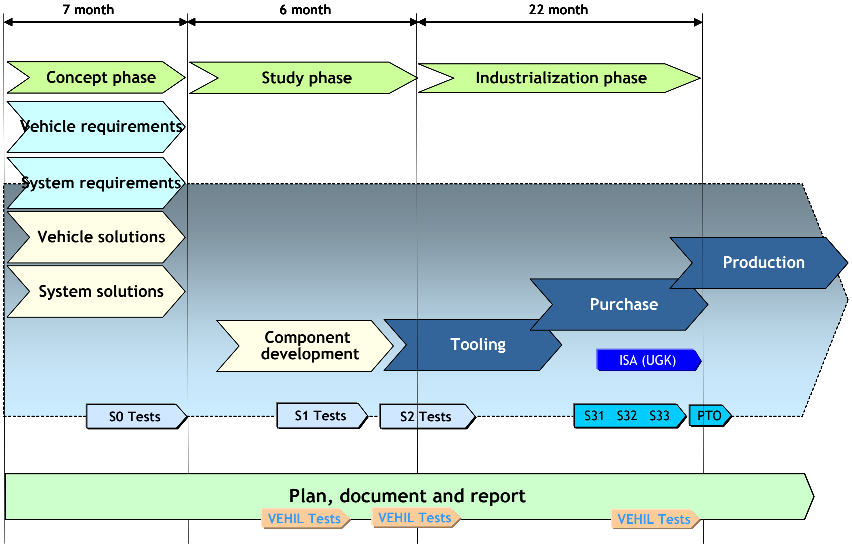

Figure 6 – Automotive development methodology

The methodology is in general characterized by three phases: a *concept phase*, a *study phase* and an *industrialisation phase*. Currently, the application of VEHIL is mainly positioned in the study phase. Developments however are directed towards the application of VEHIL as part of the so-called S2 Tests, being the final tests in the study phase, by means of defining benchmark test scenario's. At a longer term, VEHIL might also be used to perform so-called pre-tryout, tryout and pre-production tests, marking the end of the industrialisation phase.

For a detailed description of the role of VEHIL in the automotive development process, the reader is referred to [8].

5 VEHIL cases

5.1 Sensor mapping

Sensor mapping aims to provide a clear picture of the sensor performance with respect to viewing angle, accuracy and dynamic effects, based on which the sensor can be calibrated and/or improved. A VEHIL sensor mapping test can be established by simply driving the MB around the VUT according to a predefined trajectory. There need not be any interaction in this case, so it is effectively an open-loop test. As an example, consider the test as depicted in figure 7.

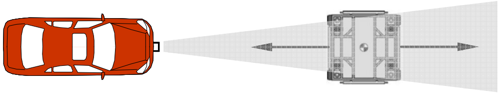

Figure 7 – Sensor mapping scenario

The VUT is equipped with a radar and the MB slowly decreases the distance to the VUT. The resulting measurement is shown in figure 8.

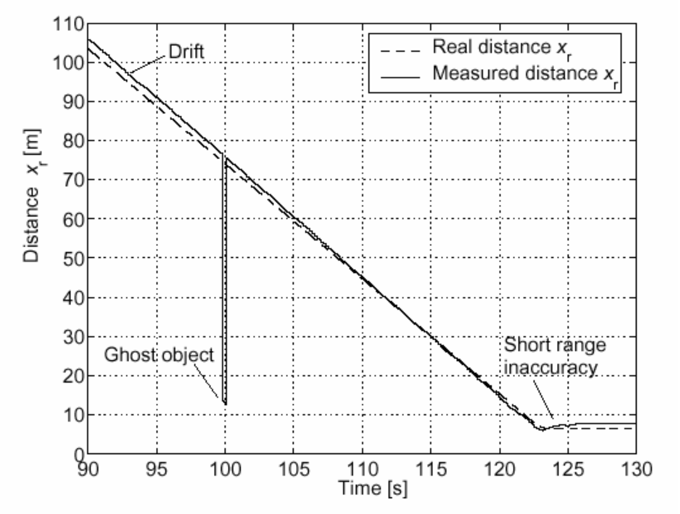

Figure 8 – Sensor mapping test results

This figure shows the distance as measured by the radar and the measured MB position with respect to the VUT as a function of time. As can be seen from the measurement, the sensor is not quite aligned with the vehicle's longitudinal axis, but, more importantly, the inaccuracy of the radar at short ranges is quantified. Finally, there is also shortly a ghost object detected at about 12 m before the VUT.

The added value of VEHIL in this test is that the accurately known MB position (within +/- 0.02 m) allows for a sound comparison between this position and the radar measurement, which means that VEHIL is an effective tool for sensor mapping. Also, the MB is a very flexible target object, capable of repeatedly driving all types of trajectories at various velocities and accelerations, resulting in a reproducible and efficient testing process.

5.2 Adaptive Cruise Control

The next case concerns a test vehicle equipped with a radar and ACC functionality. The objective of the test is to assess the dynamic behaviour of the test vehicle when suddenly an object appears. The dynamic behaviour of the entire system is targeted here, comprising radar, ACC controller and vehicle dynamics. Figure 9 shows the scenario. The first vehicle (orange) is represented by MB2 and the second one (blue) by MB1. The velocity difference between the VUT and both MB's is 30 km/hr. This test scenario is a real closed-loop test as explained in section 3.4.

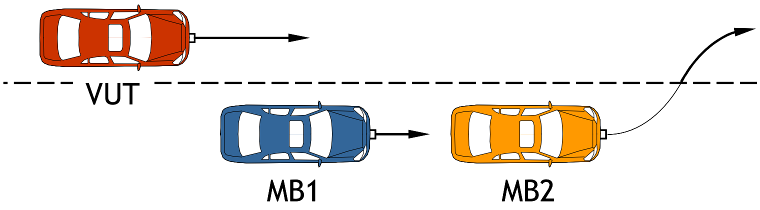

Figure 9 – ACC scenario

Figure 10 shows a sample of the test results. The upper and the middle plot show the distance and angle of MB1 and MB2 with respect to the VUT as measured by the radar and independently measured by the MB's themselves. These two figures provide a check of the radar measurement. The time response at the bottom shows the VUT velocity as a reaction to the disturbance introduced by MB2. It appears that the VUT velocity reacts in a very smooth way to this disturbance, almost without overshoot. From the upper plot, it can be seen that the minimum distance between VUT and MB2 is about 10 m.

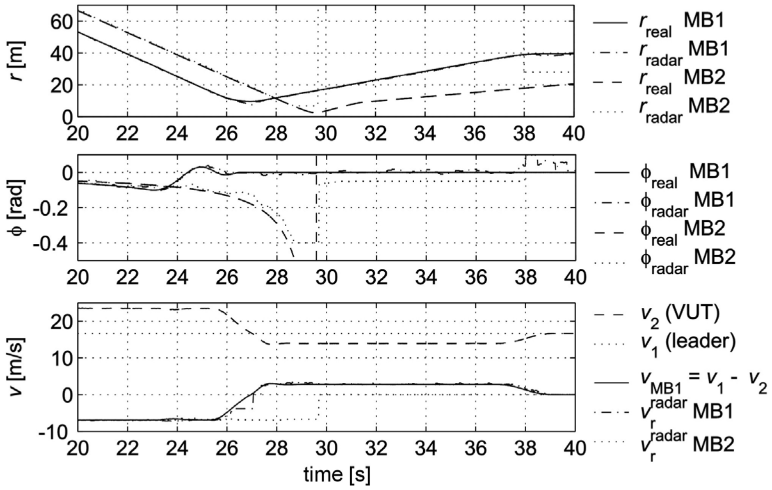

Figure 10 – ACC test results

If it is decided to adjust the ACC controller settings, exactly the same test can be done again to evaluate the effects, making use of the reproducible nature of VEHIL tests.

5.3 Collision mitigation

As a last case, some results are shown of a test concerning a VUT equipped with a collision mitigation system. The test objective is to assess the part of the collision mitigation algorithm that predicts the probability that a collision will actually occur. The notion of collision probability is introduced here in order to lower the false alarm rate: only when the collision probability is greater than a certain threshold, the system will automatically apply the brakes. As a consequence, the test scenario primarily focuses on near-miss situations, one of which is depicted in figure 11. Here the test vehicle is approaching the target with a velocity difference of 50 km/hr and a very small lateral distance of 0.3 m. In VEHIL, this means that the MB will approach the VUT with 50 km/hr, driving backwards.

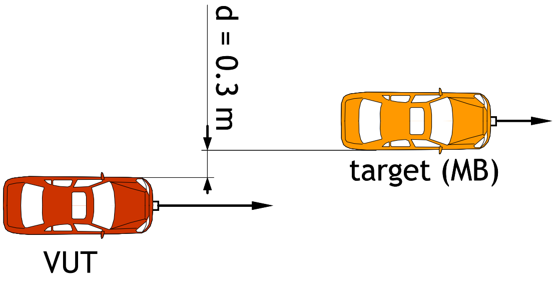

Figure 11 – Collision mitigation scenario

Given the test objective, this test can be executed in an open loop fashion, i.e. the MB drives a predefined path and will not react to the VUT. Some test results are shown in figure 12. The upper plot shows a.o. the collision probability as a function of time. As can be seen, the collision probability rises to about 70%, taking measurement uncertainties into account. This is however below the threshold, set to 95 %, so the system will not react. The upper and middle plot also show the radar range and the radar range rate respectively. From these it can be seen that a ghost object appears around t = 12 s. Although the collision mitigation algorithm reacts adequately by setting the collision probability to zero, this effect obviously compromises the system's functionality.

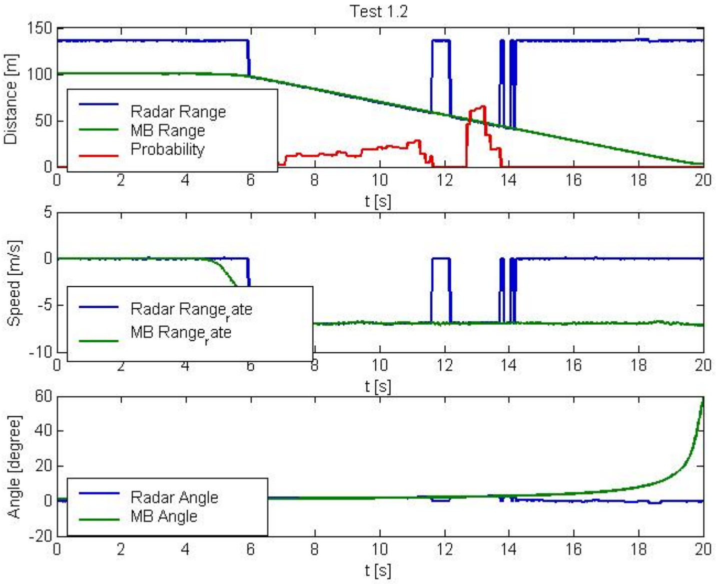

Figure 12 – Collision mitigation test results

The added value of VEHIL is that near-collision situations can be very accurately defined and executed in a reproducible manner, allowing for a fast algorithm optimisation. Moreover, these tests can be executed very safe.

6 Conclusions

Summarizing, it can be stated that VEHIL allows for testing vehicles equipped with environment sensor based ADA systems in a realistic environment which is partly simulated and partly real. In this set-up, specific problems or other technical issues can be effectively targeted in a reproducible manner. Moreover, testing is safe for man and material and a high test throughput is possible. VEHIL is applicable for various ADA systems and research questions, as illustrated by three different cases, being sensor mapping, ACC controller evaluation and collision mitigation evaluation.

The key properties of VEHIL that are responsible for the above conclusions are:

- application of relative motion, i.e. motion of other road users with respect to the test vehicle,
- the position measurement accuracy of the Moving Base,
- the manoeuvrability and high bandwidth dynamics of the Moving Base.

Further developments are primarily directed towards developing specific test scenario's and clearly linking them to the OEM's and 1st Tier development phases, ultimately resulting in a number of bench mark scenario's for sign-off tests.

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