

VEHIL – developing and testing intelligent vehicles

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VEHIL Developing and Testing Intelligent Vehicles

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Abstract

The application of driver support systems and automated (intelligent) transport systems is getting increasingly important because they have the potential to enhance the efficiency and safety of today's road transport without expanding the traffic infrastructure considerably. The high safety and reliability demands of these complex systems make their development and testing of these products an expensive and time-consuming process. This paper presents the Vehicle Hardware-In-the-Loop (HIL) simulator for a faster and more efficient development and testing of full scale intelligent vehicles and transport systems. Its technical feasibility and a proposal for a dedicated test facility are discussed. The technical feasibility has been confirmed on the basis of two functional demonstrators. The test results and experiences with these demonstrators are evaluated. It has been identified that the so-called moving bases are crucial elements of the intelligent vehicle simulator. The development of this subsystem, i.e. a high performance AGV, is the first step in the realisation of a functional full scale intelligent vehicle simulator.

1 Introduction

Vehicles and the environment in which they operate are becoming more and more complex. New functions are added and the existing ones are made more intelligent and flexible (in some cases, even automated). These intelligent vehicles equipped with, for example an Advanced Driver Assistance System (ADAS) like ACC or lane keeping, have a system boundary that lies on the vehicle level: the tyre forces control the vehicle motion and sensors (radar, vision, etc.) monitor the surrounding world. These ADA systems can still be optimised on a vehicle level by operating and testing the full scale prototype on a test track. To analyse the interactions with other vehicles, multiple prototypes and a large

development crew is necessary. The trend is to further assist the driver with new systems that will use communication to share data. This leads to interaction between intelligent systems, possibly of different manufacturers. This scenario can be expanded to more than two systems. The number of interactions increases rapidly and the global optimisation of, for example, vehicle platoons will be harder. The expansion ends in fully automated driving with autonomous vehicles in a complex environment and the control of this new transport system is influenced by a large number of parameters. The optimisation of such systems becomes highly complex and the conventional test methods will no longer be sufficient to ensure the safety.

ITS solutions have in common that they are based on new developments in the sensor and control technology as well as in vehicle technology. Figure 1 illustrates the state-of-the-art of commercially available intelligent environment sensors and gives a good impression of the complex control task that have to be fulfilled by these intelligent vehicles.

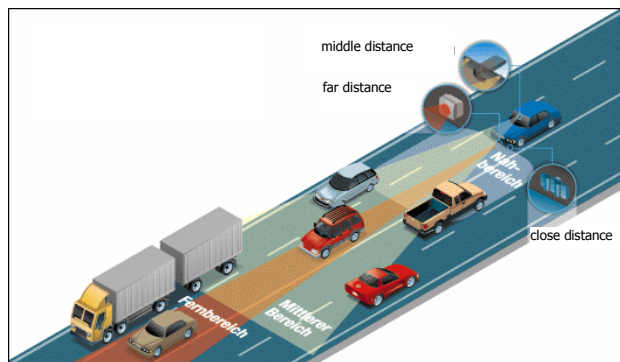


Figure 1 - Examples of intelligent environment sensors (courtesy: Robert Bosch GmbH)

New system components means elaborate testing. Furthermore, the safety and reliability demands of these intelligent systems are extremely high due to the fact that

the driver functions are (partly) automated. The development of the intelligent vehicles and transport systems requires an efficient development and test methodology for the research and analysis of the functional behaviour of the complete automated system (in terms of fail-safety, reliability, robustness, driving comfort, etc.). A proven methodology for the development of automotive mechatronic chassis systems (like ABS, active suspension, steer-by-wire, etc.) is demonstrated in figure 2.

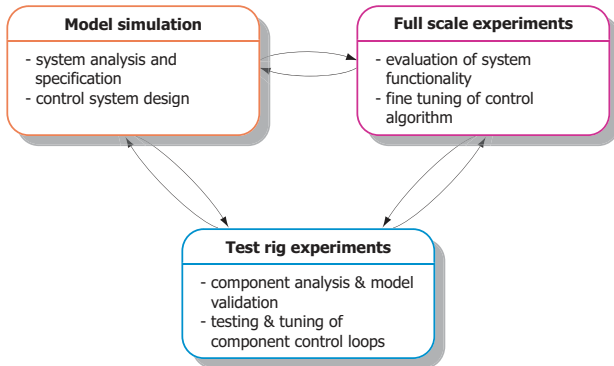


Figure 2 - The development process of mechatronic systems

The development activities can be grouped in three different clusters: ‘the development pillars’. The first pillar covers the investigation with a computer simulation model. This method is relatively cheap and is ideal for analysing and understanding the functional relationships between the components and subsystems. The first specification is often made on the basis of calculations with the simulation model. However, the correctness of the simulation results is strongly dependent on the applied structure, parameters and interpretation of the simulation engineer. To test the system behaviour and to validate the simulation results, tests with real full scale prototype vehicles are necessary. This forms the second pillar in which the human (test) driver can judge the functionality of the complete system. Due to the high system complexity and the inconstant testing conditions this pillar is the most expensive and time-consuming part of the development process. An (indoor) test rig is essential for validation of the simulation model and optimisation of the system components and the total product. This forms the third pillar. Also the development and tuning of the system controller is carried out within the three clusters.

Up to now the ‘test rig experiment’ was non-existent in the development of intelligent vehicles because the evaluation of the functionality requires the prototype vehicle to be operated in a realistic environment. In exact: the actuators have to be submitted to high vehicle speeds

and inertia loads and the sensors have to monitor the environment over large tracking distances. This involves risky outdoor full scale vehicle tests. A more refined solution is to test in a relative world (preferably indoor). This reduces the necessary space and vehicle speed considerably. As a result the safety of the test engineers is greatly improved and the reproducibility of the tests increases.

This paper presents a test methodology for full-scale vehicles and transport systems, called ‘Vehicle Hardware-In-the-Loop’ (VEHIL). VEHIL combines the HIL simulation method with a multi-agent distributed simulation environment. The latter provides for the various software and hardware interactions that are inherent to ITS. Its technical feasibility, advantages, restrictions and future developments are further explored. A successful platooning experiment was conducted with VEHIL in 1999 and was published at the IEEE-symposium 2000, see [2]. This paper presents the new developments and the expansion of the simulator in the lateral dimension. Furthermore this paper is also an introduction to the simultaneously published paper on the moving base: ‘ATS/AGV’, see [1].

2 Vehicle Hardware-In-the-Loop

2.1 System Description

The VEHIL concept allows for conducting experiments on full-scale intelligent vehicles and their infrastructure in a laboratory. First, a virtual environment is defined in which the vehicles, the infrastructure and their interactions are simulated. Next, the full-scale Vehicle Under Test (VUT) is placed on a test bench (e.g. a roller bench, providing a realistic drive line load and interfaced with this virtual environment. This is the Hardware-In-the-Loop aspect of the simulator: the unknown hardware (a validated simulation model of the new intelligent system is not available yet) is connected to a simulated environment. The VUT can be treated as a ‘black box’ of which its states (speed of travel, steering angle, etc.) can be measured and communicated to a real-time traffic simulation. One or more surrounding traffic participants are selected to be represented by a ‘real’ artefact, the so-called moving base (MB). The MB is an autonomous positioning platform that responds to open loop position commands of the traffic simulator. The MB carries out the relative motions to the VUT, that are in high correlation to the throttle and steering actions of the VUT. The VUT environment sensors monitor the MB reactions which

closes the HIL control loop: the VUT board computer thinks that he is actually driving the vehicle! Figure 9 nicely illustrates the described VEHIL concept.

VEHIL reduces the amount of full-scale hardware needed for an experiment. Furthermore, a hardware test on a test track would require the proper infrastructure components, instrumentation of several vehicles, test drivers, extensive safety precautions, transportation to and from the test track, acceptable weather conditions, and so on. Any modifications in the hardware or controllers as imposed by the experiment results should be performed on all vehicles or infrastructure. Using the VEHIL concept, vehicles and vehicle systems can be tested in a safe and controlled way. The only moving objects are dedicated hardware systems representing the relative motion with respect to the VUT. These are well understood and thoroughly tested parts of the simulator and equipped with safety systems.

2.2 Longitudinal Application

To confirm the technical feasibility of VEHIL, a demonstrator has been built by TNO Automotive. Figure 3 shows some pictures of the developed VEHIL elements. A platooning experiment was selected to serve as a pilot case. The upper drawing in figure 3 shows that the simulated platoon consists of 8 passenger cars of which the fourth and fifth vehicle were represented in hardware (indicated with the dashed box) for the VEHIL experiment. The platoon controller was developed in a numerical simulation environment and practically implemented in a conventional midsize passenger car. The vehicle was modified with throttle and brake actuators and placed on a roller bench, simulating the longitudinal inertia and rolling resistance forces on the drive line of the VUT. The measured behaviour was evaluated in terms of robustness and performance. For a detailed description of the experiment and the measurements see [2]. In this case only the longitudinal behaviour of the (vehicle) platoon was considered. All the vehicles in the platoon were equipped with throttle and brake actuators, a headway sensor and a receiver for vehicle to vehicle communication with the platoon leader (the first vehicle). The environment of the VUT was animated by a robot vehicle (small industrial AGV), the so-called moving base (MB). The rear end of a VW Golf was placed on the robot in order to provide a realistic reflection for the laser based headway measurement. The platoon controller uses a speed depended headway. To enhance the quality of the various headway controllers and thus the stability of the complete platoon, also the

speed of the platoon leader is communicated to the following vehicles.

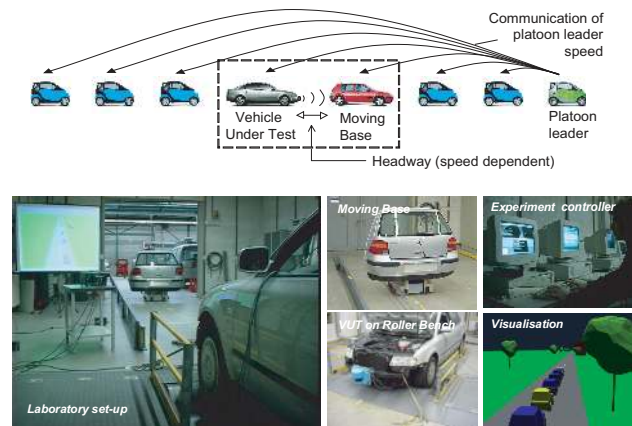


Figure 3 - The first VEHIL demonstrator: "platooning"

The results of the VEHIL platooning experiment clearly showed that it is technically feasible to implement the concept of an intelligent vehicle hardware-in-the-loop simulator for testing with a full-scale vehicle. The link between simulation and actual driving tests has been made, because all hardware characteristics were included in the experiment. This automatically implies that all unknown component properties might hamper the functionality. These unexpected hardware effects are mostly of a non-linear nature (like friction) and are usually not covered by any available simulation model of the new intelligent system. Due to the conditioned laboratory circumstances and the reproducibility of the tests, it was possible to isolate different hardware influences on the behaviour of the controller, and deal with them separately [2].

2.3 Lateral Application

To confirm the feasibility of VEHIL for investigating the behaviour of free manoeuvring autonomous vehicles (longitudinal and lateral components), an electric, rear wheel driven prototype AGV of the Underground Logistical System (OLS) [4] was tested in a VEHIL setting. Figure 4 shows a picture of the OLS vehicle with its rear wheels placed on a roller bench.

The OLS vehicles can navigate autonomously with the use of an antenna that measures a grid of magnets which are regularly distributed over the floor at known locations. The position of the AGV is calculated with an odometric model of the vehicle, fed by the sensor signals of the wheel rotations and steer angles (encoders). The combination of the odometric information and grid

information provides a robust position measurement system. To enable a successful VEHIL experiment, both sensor inputs must be simulated. The encoder signals are already available in the vehicle hardware. The rear wheels are placed on a roller bench, providing free rotation of the driven wheels. The front wheels are lifted, enabling the steer actuators to control the orientation of the wheels. For the correct grid information a special grid simulator had to be developed.



Figure 4 - The OLS prototype vehicle on the VEHIL test bench

2.3.1 Grid Simulator

The grid simulator is shown in figure 5. It basically consists of a driven axle on which three discs are mounted.

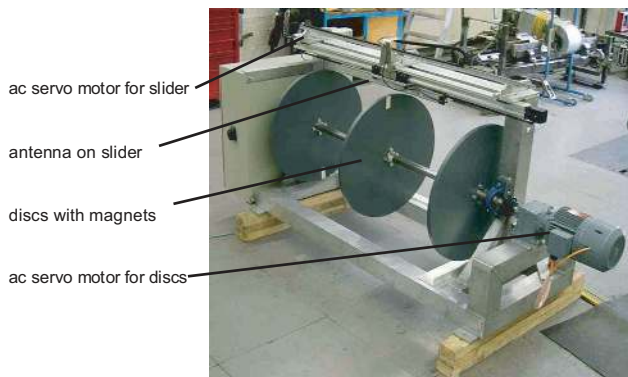


Figure 5 - The grid simulator

Magnets are attached on the circumference of the discs, providing three parallel tracks. The electric motor that controls the rotation of the discs simulates the longitudinal displacement of the OLS vehicle. The lateral

displacement is carried out by a linear slider that moves in traverse over the magnet discs. The radius of, and the distance between the discs were chosen in a such way that the same grid dimensions are obtained as used in the actual testing of OLS. The amount of discs limits the lateral displacement that can be evaluated. The antenna was disconnected of the test vehicle and attached to the slider. The complete setup of the lateral demonstrator is shown in figure 6.

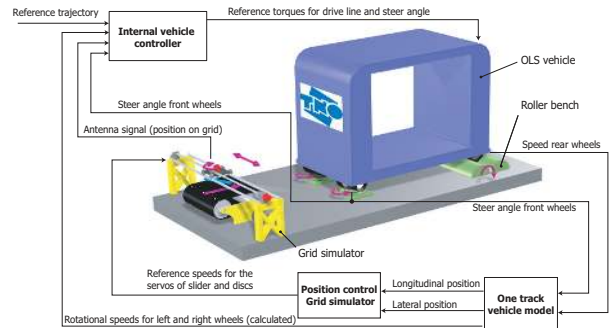


Figure 6 – Principle of operation of the VEHIL lateral demonstrator

The actual position of the AGV is calculated (real-time) with the use of a validated simulation model of the vehicle. Due to the fact that the two rear wheels of the OLS vehicle are coupled by the drums of the roller bench, the so-called one track ‘bicycle’ model (see [7]) is sufficient to calculate the dynamic manoeuvring behaviour of the VUT. The average value of the two AGV rear wheel encoder signals and the measured effective steer angle were used as an input for the applied non-linear tyre model (Magic Formula covering the combined cornering and braking behaviour, see [6]). The computed slip forces causes the real-time simulation model to move over a certain path. The lateral motion is merely induced by the steering motion of the steer angle servo rather than by differential driving torques between the left and right wheels. To provide the internal vehicle controller with the correct odometric information on the state of the vehicle, the speeds of rotation of the rear wheels (they differ during cornering) are calculated on the basis of the translating and yaw velocities of the simulation model. The simulated position of the vehicle model is used as a reference for the controller of the grid simulator. As a consequence the antenna tracks the motion of the vehicle model. The measured antenna signal (as well as the measured steer angle of the front wheels and the calculated rotational speeds of the rear wheels) is used as a feedback by the internal controller of the OLS-vehicle, enabling the ‘black box’ board-computer to control the motion of the simulation model.

As a result the velocity of the discs corresponds to the speed of travel of the test vehicle and the traverse displacement of the slider to the lateral motion of the AGV.

2.3.2 Test Results

With the lateral VEHIL test rig a set of experiments were conducted. First the straight line driving behaviour was evaluated. To illustrate the function of the antenna, a measurement with and without the grid simulator was carried out. The odometric information was available in both cases. The results of these tests are shown in figure 7.

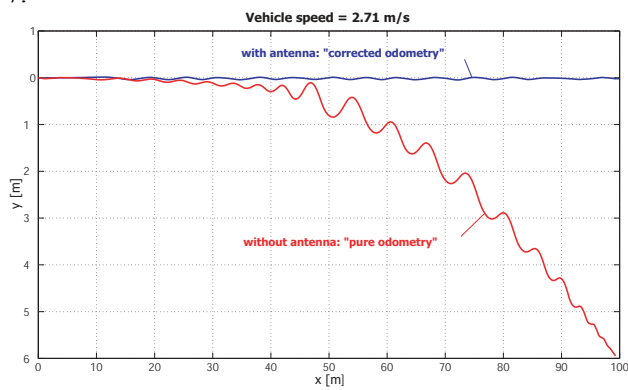


Figure 7 - 100 m straight line driving with and without grid simulator

Figure 7 clearly shows that the vehicle without the information of the magnet grid drifts away laterally by 6 metres when travelling over 100 metres in the longitudinal direction. For the tests all odometric parameters like wheel base, track width, effective rolling radius of the vehicle simulation model and the odometric model of the vehicle tracking controller were geared to one another. Despite this effort a lateral drift from the reference path could not be avoided in case of the antenna-less vehicle. This is the result of little differences between the models used (cornering stiffness, steering geometry, etc.) and the resolutions of the vehicle encoders. The additional feedback position information from the grid simulator allows the vehicle controller to keep the vehicle on the desired track. A strange (low frequency) undulation on the realised path is visible in the figure. A closer look at this phenomenon shows that this is the result of (actively generated) steer angles. A more thorough analysis indicated that the steer servo was tuned rather 'soft', making the position controller of the front wheels prone to disturbances. Normally, the self-aligning torque's of the tyres and steering system help to position the wheels.

The tests of figure 7 were carried out for a speed of travel of 2.71 m/s. To investigate the stability of the vehicle at higher speeds, several tests with increasing vehicle speeds at straight line driving were executed. At a speed of travel of $v = 4.71$ m/s the vehicle motion became unstable, probably related to the above mentioned 'soft' steer servo. The positive point of this test was that this dangerous experiment was performed in the safe and controlled environment of VEHIL: The OLS vehicle, weighing 5000 kg, was standing still at the roller bench while the simulation model was leaving the track at 'high speed'.

To analyse the performance of the VUT controller under cornering condition, slalom drive tests were carried out at different vehicle speeds. Moreover, this test demonstrates the ability of VEHIL to research intelligent vehicles that are free manoeuvring, represented by the lateral and longitudinal motion. Figure 8 shows the test results. The dashed line represents the path to be followed. The sine-shaped slalom course has a wave length $\lambda = 30$ m and an amplitude $A = 0.6$ m. The 30 m long stroke in front of the slalom was used to accelerate from standstill up to the desired driving speed, allowing the vehicle to drive the slalom at a constant speed of travel. In figure 8 the results of three test drives are collected. The solid curves are the actual paths of the vehicle at the speeds of travel: $v = 0.76$, 1.73 and 2.71 m/s. The general impression is that the higher the speed is, the more difficult it is to keep the OLS vehicle on the reference track. At vehicle speeds $v = 0.76$ m/s and $v = 1.73$ m/s the reference path can be followed adequately. Although the curve for $v = 1.73$ m/s shows a small undulation at the amplitude of the path. The vehicle motion for a speed of travel $v = 2.71$ m/s has very poor damping and its behaviour is can be judged unstable. The safe environment of the VEHIL experiment allowed the slalom to be driven at even higher speeds. As expected the vehicle controller was not capable to keep the AGV on its track. Apparently, the 'soft' steer servo can not cope with the required dynamics for cornering at higher speeds of travel.

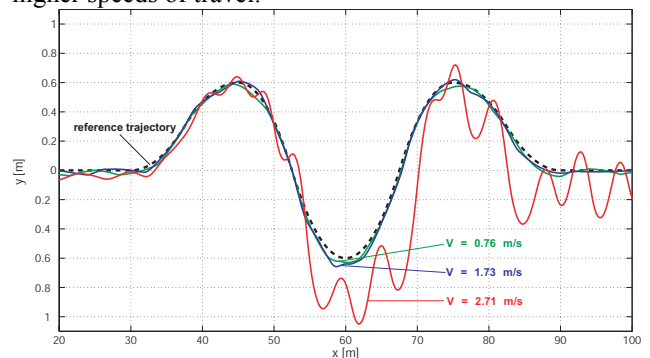


Figure 8 - Test results of slalom driving

3 Proposal for a Dedicated VEHIL Facility

The technical specifications that are posed to a professional VEHIL test facility are the most demanding in the case of automotive applications. Especially, the needed hardware for the physical simulation of the AGV sensors (in terms of a realistic excitation) is very complex in this case. The complexity of the VEHIL setting is dictated by the functionality of the intelligent vehicle which has to be tested. The required VEHIL specification depends amongst others on:

- The physical principles of the used sensor systems (radar, laser, camera, etc.);
- The bandwidth of the AGV control system;
- The dynamics of the actuators;
- The vehicle speeds.

The new VEHIL test setting has to be designed in such a way that the number of restrictions to testing the AGV (= VUT) functionality is minimised and that the amount of interactive manoeuvres between the VUT and the moving bases (= dynamic environment) is maximised. In this chapter a proposal for a professional VEHIL test facility will be discussed.

3.1 Global Concept

Figure 9 shows an ‘artist’s impression’ of the proposed VEHIL test facility. The test bench for the VUT will be installed centrally in a large hall, typically sized 200 × 50 meter (length × width). A lower cost-intensive alternative is to partly cover the test area. The hall is divided in three or more parallel lanes. The test bed of the VUT can be a roller bench or more advanced, so-called Flat Tracs (manufactured by MTS System Corporation, see [5]). The flat surface roadway technology of MTS allows the driven wheels to be steered, providing a realistic load on the drive line as well as on the steer actuators. The immediate environment of the VUT is occupied with manoeuvring look-alikes of fellow road users (passenger cars, lorries, cyclists, etc.), represented by the moving bases.

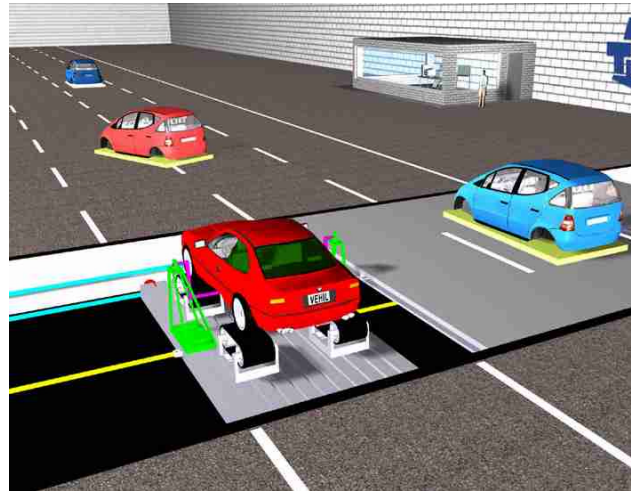


Figure 9 - ‘Artist’s impression’ of the future VEHIL test facility

The moving bases are automatic guided vehicles disguised as conventional vehicles. These mobile robots simulate the motions of specific traffic participants relative to the VUT. To be able to carry out the complex manoeuvres associated with the relative motion in VEHIL, the moving base must have an extreme freedom in manoeuvrability. For instance, for the simulation of a split-and-merge action in a vehicle platoon, the robot vehicle has to carry out crab wise motions. This requirement has an high impact on the drive line and steering concept of the AGV. Moreover, its dynamic response on position commands has to exceed the handling performance of modern road vehicles considerably. How this is solved, is described in the paper on ATS/AGV, see [1].

The so-called experiment controller is the heart of the VEHIL setting. The experiment controller is based on a Multi Agent Real-Time Simulator (MARS), see [3]. As a matter of fact this experiment controller is a framework of computers that is capable of calculating a traffic flow with multiple vehicles and other objects of the infrastructure in real-time. The main feature of the MARS is the fact that the interactions between the entities (objects in the virtual world) are dynamical in nature. Within the MARS framework a complete virtual absolute world is created and directed. The MARS also calculates the relative motions between the moving bases and the VUT. An overview of the VEHIL working principle is given in figure 10.

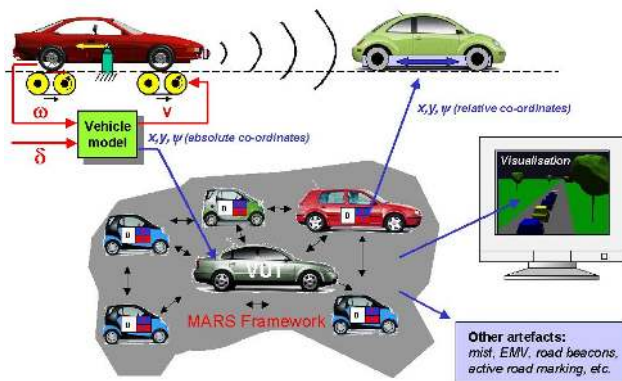


Figure 10 - The VEHIL principle of operation

The MARS is an essential part of the VEHIL simulator. In order to be able to calculate the interactions between the VUT and the other virtual vehicles (within the MARS), information on the motion of the VUT is required. This information can be obtained from a dynamic vehicle model of the vehicle under test. This simulation model uses the measured state signals, like wheel speed and orientation (steer angles), as inputs. The tyre model calculates the slip forces that act on the vehicle. As a result the simulation model starts to move resulting in changes in the longitudinal, lateral and yaw co-ordinates of the vehicle body. These signals are communicated to the MARS which on his turn calculates the desired relative position of the moving base to the VUT. The VUT headway sensor monitors the reaction of the moving base which closes the VUT autonomous driving control loop. The calculated signals of the tyre model also can be used for the control of the Flat Tracs, enabling a relatively easy simulation of variations in the friction characteristics of the adhesion forces between the tyre and road.

Apart from the control of the moving bases, the MARS is also capable of controlling other artefacts or disturbance sources, like fog, active road marking, etc. Also a real-time visualisation of the virtual MARS world is provided. This is a powerful tool in the analysis of complex interactions in the tested traffic stream. The visualisation helps the researchers to interpret of the manoeuvres.

3.2 Advantages and Restraints of VEHIL

The main advantages of developing intelligent vehicles with VEHIL are its contribution to a highly efficient development process (reduction in time, costs and number of prototypes) and the high manageability and reproducibility of complex experiments. VEHIL also enables a better transition between simulation and full

scale road tests. And last but not least, VEHIL guaranties high safety for testing personnel and prototypes.

The added value of VEHIL becomes less when the nature of the test that is carried out is getting closer to a real hardware test in the field. This is a direct result of the increasing difficulty of creating an relative world that is becoming more and more complex when new elements are being added to sophisticate the sensor inputs and actuator loads.

Known areas for further research are the testing of vision based systems and control systems that use the information from state sensors, related to inertia forces on the VUT (e.g. lateral acceleration, yaw rate, etc.). These limitations can be dealt with and compensated for on a case to case basis. For example, the inertia forces on the sensors can be simulated by placing them on actively controlled tilting and rotating tables. The control of these special test rigs is carried out by the VEHIL simulator. A last resort is simply simulating these sensor signals. Furthermore false reflections of radar signals from the walls of the VEHIL facility may have a disturbing influence on the vehicle controller. The severity of this problem depends on the robustness of the autonomous system. It can be stated that intelligent vehicles have to keep on functioning while driving through tunnels and under bridges. A more comprehensive analysis of the restraints of VEHIL testing is beyond the scope of this paper.

4 Future Steps

Recent work has involved building a new moving base with updated specifications; this was ready by the beginning of 2002. The VEHIL project commenced in late 1998 and the first two years were devoted to performing feasibility studies. In the course of 1999, the first demonstrator – for longitudinal motion – was ready for release. TNO also applied for a patent at that time. The Dutch patent and the international patent are pending. In 2000 a demonstration of a VEHIL test covering the longitudinal and lateral motion of an industrial AGV was performed. In 2001 TNO moved on with the development of the first high performance moving base. An extensive discussion of the VEHIL moving base is given in the paper *ATS/AGV - Design, Implementation and Evaluation of a High Performance AGV* [1]. In 2002 TNO will perform contract research on intelligent vehicles in a VEHIL setting using the new moving base in combination with a conventional roller bench. The ultimate goal is to build a full-scale VEHIL facility (covering Flat Tracs)

that will be put into operation by 2010. In the meantime the large hall for the VEHIL simulator will be build and is planned to be available for VEHIL testing (with dedicated roller benches) in 2003. TNO Automotive has been awarded a considerable subsidy from the Dutch Ministry of Economic Affairs for these developments.

5 Conclusions

With VEHIL the functionality of intelligent Vehicles can be tested by “driving the complete vehicle in a relative world”. This is achieved by submitting the vehicle to realistic sensor inputs and realistic actuator loads. Elimination of the vehicle speed makes complex experiments more manageable, more reproducible and safer. As a result the efficiency of the development process is greatly enhanced. This results in shorter development time, less prototypes and ultimately, lower costs. Furthermore, VEHIL contributes to a better transition from the simulation design activities to testing the full scale prototype on the road.

The feasibility of VEHIL was convincingly confirmed by the realisation of two functional demonstrators, covering the longitudinal and lateral motions of autonomously driving vehicles. The test results showed that unexpected hardware properties, like friction, have a serious influence on the stability of controllers that were tuned on a simulation level only. In the safe environment of the VEHIL setting these instabilities could be recognised and dealt with in an early stage of the controller system design.

Acknowledgments

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