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Hardware-in-the-Loop Testing of Vehicle Dynamics Controllers – A Technical Survey

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ABSTRACT

Hardware-in-the-loop (HIL) test benches are indispensable for the development of modern vehicle dynamics controllers (VDCs). They can be regarded as a standard methodology today, because of the extremely safety-critical nature of the multi-sensor and multi-actuator systems used in vehicle dynamics control. The required high quality standards can only be ensured by systematic testing within a virtual HIL environment before going into a real car.

This paper aims to provide a condensed technical overview of state-of-the-art HIL test systems for VDCs, which are currently widely used in passenger cars, in the form of ABS and TCS, as well as ESP, or integrated chassis control, which is just coming onto the market. First, a short introduction to the basic functionality of these types of ECUs is given, and the reasons why HIL testing is necessary and especially useful for VDCs are discussed. Since most of the dominant suppliers of VDC systems like Bosch, TRW, and Continental Teves, have the same principle system architecture, the closed loop HIL system (including I/O interfaces, signal conditioning, real-time models, user Interface, and test automation) can be generalized. However, there is still a possibility depending on the module being tested that one must include module specific resources to the setup.

A more detailed description of the currently used sensor signals for steering wheel position, lateral/longitudinal acceleration, yaw rate, wheel-speeds (active/passive/ intelligent) and the hydraulic pressure sensors (internal/external) is presented. For the synthetic simulation of these signals within a simulator setup, it is also necessary to take into account the diagnostic functions of the ECU, for example to properly simulate the self-adjusting procedures for some of these sensors.

Controlling brake forces at each wheel is the main task of such a system and it is normally performed by hydraulic valves actuated by solenoids. Since these devices are enclosed within the housing of the ECU itself, a special device, called a valve signal detection unit (VSD), is used to measure the valve actuation.

In order to close the loop, a model of the complete vehicle is required to provide consistent and precise sensor signals as a response to the current actuator and (simulated) driver input signals. Some parts of the model will be explained in more detail to show how it is possible to overcome the partly numerically stiff behavior of the governing equations and to emphasize their importance within test scenarios and standard test maneuvers.

In the last section of the paper, an example of the interactivity of systems like ESP, EPB (electrical parking brake), and ACC (automatic cruise control) will show how demanding today's chassis controls are and how HIL technology copes with these challenges.

INTRODUCTION

The history of hardware-in-the-loop (HIL) simulation in automotive engineering goes back to the 1980s. To begin with, HIL was widely used for testing individual components (e. g., new actuators for active suspensions), mainly in universities and research or advanced engineering departments. In the 1990s, an increasing number of electronic control units (ECUs) began to be installed in vehicles, and there was greater emphasis on testing these ECUs. The ECU itself was now the object under test. HIL test systems were increasingly used not only in advanced engineering and control design, but also in production development, where they gradually replaced the open-loop or stimulus simulators that were still prevalent at the time. The main focus of these black box tests was on function verification, and on testing self-diagnostics and hardware, to support production-level verification by automated regression tests. The number of ECUs in vehicles as well as their networks continued to rise throughout the 1990s. The breadboards that were used to test the ECUs proved to be inadequate to test these networks leading to an increase in the quality assurance problems. As a result, the breadboards were increasingly replaced by laboratory vehicles (= networked HIL systems connected to networked ECUs [1], [2]) allowing automated testing of the complete ECU network including ECU variants. The result was a considerable improvement in quality with regard to distributed functions and inter-ECU communication.

The introduction of anti-lock braking systems (ABS) in production vehicles in 1979 by DaimlerChrysler made it possible to prevent the wheels from locking during braking maneuvers. This not only ensured that the vehicle remained steerable, it also allowed optimum utilization of the friction coefficient between the tires and the road surface, thereby reducing braking distances. The essential function of the ABS ECU is to use wheel speed to detect when the maximum static friction has been exceeded and if necessary reduce brake pressure at the wheel brake cylinders via magnetic valves to prevent the wheels from locking. The first HIL test systems for ABS ECUs were built at the end of the 1980s [3]. As these first ABS systems were optimized and HIL technology continued to develop, the mid-1990s saw a whole series of publications on the subject [4], [5], [6], [7]. Among other things, these illustrate how the spread of HIL was supported by increased processor performance, and also by special HIL hardware for I/O (e.g., fast wheel speed signal generation).

With a pure ABS system, the driver is largely dependent on steering to prevent under- or oversteering of the vehicle in a µ-split braking maneuver (in which the left and right vehicle sides have different friction coefficients). The obvious next step was to try to actively superimpose a stabilizing yaw torque on the vehicle by applying separate brake pressures to each wheel. In the mid-1990s, the first VDC/ESP (Vehicle Dynamics Control, Electronic Stability Program) systems were installed in production vehicles (DaimlerChrysler, March 1995). One of the early HIL systems for testing ESP ECUs at Audi [8] was based on a multiprocessor system with 5 DSP processors that computed the models for the powertrain, front/rear suspension, and front/rear wheels separately. The brake hydraulics were integrated as a real system with a pedal actuator, among other reasons because the processing power for computing brake hydraulics in real time was not available at that time.

Progress from the original ABS to ESP with integrated TCS (traction control system) and BAS (brake assistant system) presented HIL simulation with new challenges with regard to the sensors, actuators, and models.

ESP generally involves yaw rate and side slip angle controls that complemented one another. The VDC system achieves this by computing the reference values for the yaw rate and side slip angle via a single-track model with a simple tire model, whose inputs consist of the engine torque (from the engine management via CAN) or the vehicle speed, the brake pressure (pressure sensor in the hydraulics), and the steering angle (CAN node). A Kalman filter (estimator) can be used to determine the actual values for the yaw rate and the side-slip angle by means of a simple two-track model if the yaw rate and lateral acceleration are also additionally captured. A PID controller uses these values to compute a stabilizing yaw torque that is implemented by the underlaid wheel slip controller (Fig. 1).

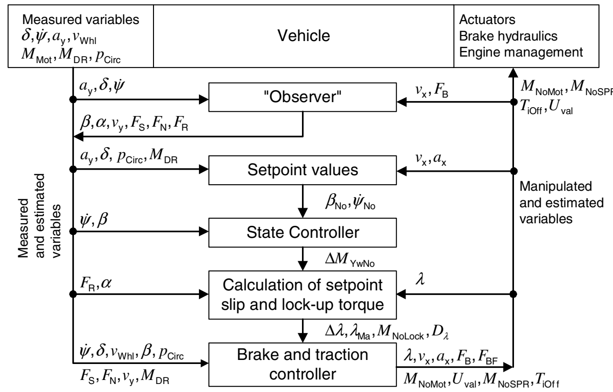

Figure 1: Functional architecture of VDC systems [9], [10].

The specific sensors and actuators commonly used for vehicle dynamics control, and the associated interfaces for HIL simulation, are described in greater detail in the section below.

The following section gives an outline of the necessary simulation models and appropriate modeling tools. Implementation aspects of real-time simulation are discussed, with some numerically critical submodels as examples.

The Applications chapter describes the design concept and hardware structure of current VDC HIL systems for a single ECU and for an ECU network. Additionally, HIL systems for EPAS and ACC systems are introduced in more detail. The final chapter discusses future challenges to HIL simulation by presenting current development trends in vehicle dynamics control (integrated chassis control, ICC).

I/O INTERFACES OF VDC SYSTEMS

The sensor and actuator signals that are typical of vehicle dynamics control system are shown in Fig. 2:

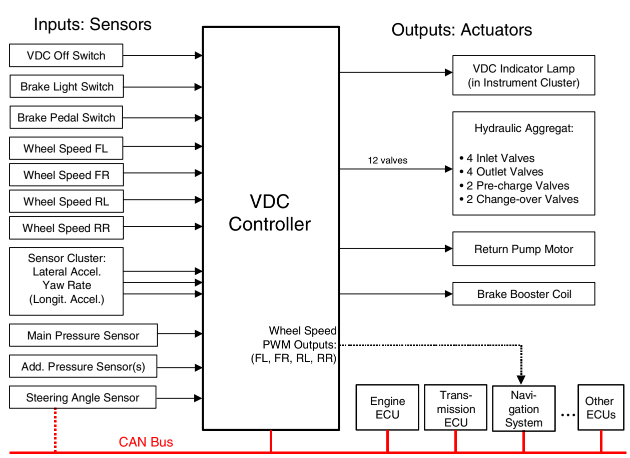

Figure 2: Overview of the sensors and actuators of a VDC system.

SENSORS

Vehicle dynamics control systems are extremely safety-critical components, so monitoring their sensors has high priority, from the point of view of both the electrical interface (current interface instead of voltage interface) and the signal interface (plausibility check using auxiliary variables). The most important sensor types are described below.

Steering Angle Sensor:

The steering angle is generally measured at the steering column and transmitted to the VDC system via the powertrain CAN bus. An alternative is to use encoder-type sensors, having two signals with a 90° phase shift (to detect the direction of rotation) directly connected to the VDC. To make the signal plausible, the steering angle sensor is given the necessary information during initialization. Zero position (= straight ahead) is when all 4 wheel speed sensors measure the same speed (within narrow confines). In addition, the steering angle sensor and the VDC module in each vehicle have to be made known to each other via a diagnostic device. This is done at the end of vehicle production, or later in a garage, e.g., when one of the two components has been replaced.

In HIL simulation, the steering wheel angle is determined in the driver model or in maneuver control. The sensor is simulated by generating either the appropriate CAN messages (CAN sensor) or a suitable encoder signal (e.g., by means of a fast signal processor, slave DSP).

Sensor Cluster:

To capture the lateral acceleration and yaw rate, sensor clusters are used. These are micro-mechanical devices that are usually located in the middle of the vehicle, close to the center of gravity. The variables that are captured, together with the wheel speeds, enable the VDC system to determine the actual movement of the vehicle (e.g., wheel-slip and side-slip angle). The vehicle's actual longitudinal speed is computed from the speed of the driveless wheels. As this is not possible with all-wheel-drive vehicles, the sensor cluster in these includes a sensor for longitudinal acceleration. The sensor cluster is connected to the VDC module either via a private CAN bus or via discrete lines. In either case, extensive initialization sequences are performed before the VDC system starts running. In some systems, these sequences can be repeatedly initiated by the VDC module, even while it is running. For plausibility checks, values such as the ratio of yaw rate and steering angle are used (when the vehicle moves slowly in a circle, a constant ratio emerges) as a reference. If the sensor cluster is a real component in the HIL system, correct positioning is essential, as otherwise gravitational acceleration is interpreted as constant lateral or longitudinal acceleration.

The variables longitudinal and lateral acceleration, as well as the yaw rate, are determined in the vehicle dynamics model, and must be fed to the VDC module in a suitable form. A sensor cluster with discrete signals can be simulated relatively simple via appropriate analog outputs. Far more work is needed for the CAN version. Via a private CAN bus, the VDC module starts an initialization process (initialization protocol, often proprietary for security reasons), to which the sensor cluster must react. A possible solution in HIL systems is to establish communication between the real VDC module and the real sensor cluster via the simulator, using a CAN gateway. The simulator reads in the initialization messages on a CAN channel, and outputs the data bytes directly and unchanged on a second CAN channel. In contrast, in normal operation the CAN messages from the sensor cluster are manipulated by insertion of the simulated variables longitudinal and lateral acceleration and yaw rate before being passed on to the VDC module. Fig. 3 shows the basic principle, and Fig. 4 an excerpt from the model.

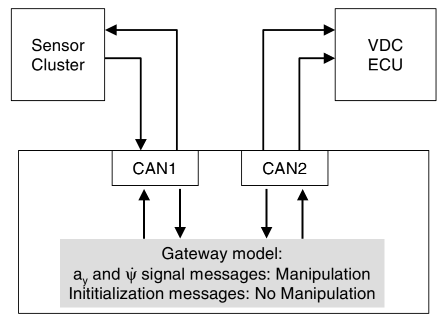

Figure 3: Sensor cluster gateway.

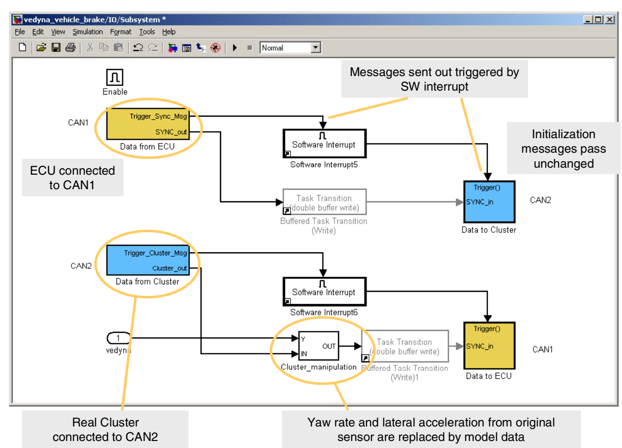

Figure 4: Sensor cluster gateway model for the manipulation of the cluster messages.

Brake Pressure Sensor:

The hydraulics aggregates have internal and/or external brake pressure sensors. However, both the pressure in the main brake cylinder and the brake pressures in the individual brake circuits are important measurement variables for the VDC system, so after the system is switched on, extensive initialization procedures are performed (again initiated by the VDC module), in which the sensor reports values that are intentionally outside the

valid range several times in succession (out-of-range check) or that have a specified time behavior. Some VDC systems additionally have combined sensors that alternately transmit the brake pressure and the membrane temperature (multiplex signals). The brake pressures are computed in the brake hydraulics model and generated via analog outputs of the simulator. If the VDC module has internal pressure sensors, the valve flow capture has to be suitably prepared to stimulate them (see Fig. 7, Valve signal detection unit).

Wheel Speed Sensors:

In VDC applications passive, active and active intelligent wheel speed sensors can be distinguished. Passive sensor of variable reluctance type just generate a sinusoidal voltage signal and have been now replaced more and more by active sensors with a current interface (7/14 mA or 7/14/28 mA) which are less sensitive to signal noise and disturbances. Both sensor types generate a signal where the frequency is proportional to the wheel speed. One current development is active, intelligent wheel speed sensors, for example, based on the Infineon TLE4942 Hall IC (Bosch ESP). Sensors from Continental Teves function in a similar way (Fig. 5).

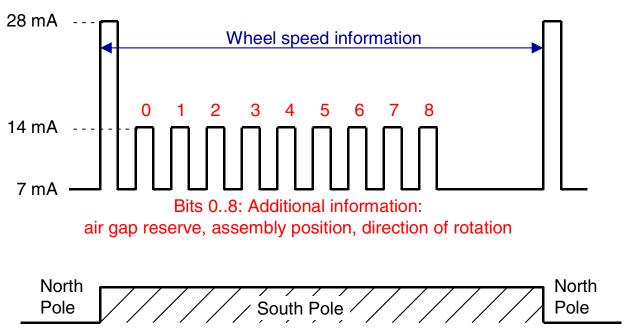

Figure 5: Protocol example of active intelligent wheel speed sensors.

These sensors have their own extensive diagnostics. The wheel speed data (frequency) is encoded in the 28-mA pulses, and the 7-mA and 14-mA pulses are used to transmit additional data by means of Manchester encoding. The additional data includes the air gap reserve, the assembly position, and the direction of rotation.

The wheel speed values for the individual signals for the sensor simulation are calculated in the wheel model. For the protocol for the active wheel speed sensors a slave processor running with a signal sample rate of approximately 4-6 µs is applied. This sample rate is required to achieve a good speed resolution even at high speeds of more than 300 km/h.

Additional inputs to the VDC module include the VDC off button, which can be used to switch off the ESP, brake light and brake pedal switches, and coding pins that can be used for hardware coding of the vehicle configuration (engine, transmission, etc.) in the wiring harness of the VDC module.

ACTUATORS

The actuators of a VDC system consist of the solenoids for controlling the valves of the two brake circuits and the return pump. Fig. 6 shows a hydraulics aggregate with the ECU and the solenoids (left), and the hydraulics block with the return pump. Another actuator is the brake booster coil, which is located in the brake booster.

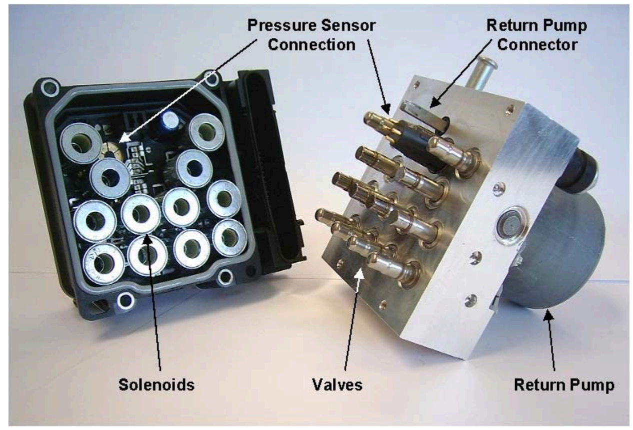

Figure 6: Hydraulic aggregate of an ESP system with solenoids, valves, and return pump.

Valve System

Today's VDC systems are implemented as hybrid technology in an integrated ECU, that is, the actual controller, the power stages and the valve coils are integrated in a plastic enclosure and mounted directly on the brake hydraulics block (Fig. 6). Similar configuration can be found also in transmission ECUs [11]. The problem for HIL simulation is that the electric control signal of the actuators (valves) cannot be captured directly. Instead, the solenoid current or the resultant magnetic field is determined by means of a valve signal detection unit (VSD) based on continuous Hall sensors.

Fig. 7 shows a VSD unit for two different ECUs. The metal pins shown contain the Hall sensors, whose output signals are amplified by signal conditioning inside the VSD enclosure. The VSD unit passes the captured solenoid signals on to the HIL simulator, where they are used as inputs for the brake hydraulics model. Fig. 7 also shows the spring pins used as contacts for the integrated brake pressure sensors, at top right.

Earlier valve systems basically used only switching valves, but today continuous valves are also used. This means that it is generally no longer sufficient to simply detect on and off states. Instead, the solenoid current (or the magnetic field) must be measured precisely by the Hall sensors, which requires good alignment of the magnetic field with the Hall sensor.

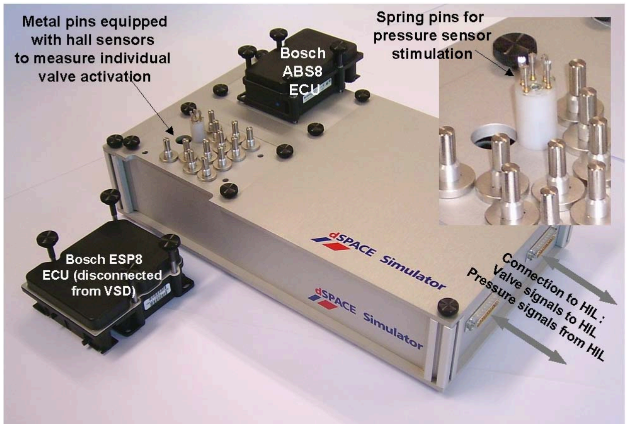

Figure 7: Valve signal detection (VSD) unit for two different VDCs (Bosch ESP8 and Bosch ABS8).

Return Pump

The return pump (see Fig. 6, right) is controlled directly by the VDC module. It ensures the necessary brake pressure in the event that the driver does not use the brake pedal (VDC intervention). The pump motor is specified for currents of up to 80 A, and the brief period of shutdown delay (in the ms range) for which the motor continues running when the ECU is switched off is used to diagnose defective pumps. Thus, for use in the HIL system, either a real pump motor can be installed, or alternatively, a substitute circuit (RC circuit) on the simulator's load boards, which has the same mechanical time constant as the real motor.

Brake Booster

Brake assist functionality requires high brake pressures to be reached fast, e.g., for panic braking, even if the driver does not apply much force on the pedal. Panic braking situations are detected via a fast pressure rise in the main brake cylinder or via a membrane position sensor in the brake booster. In this case, the VDC module actuates a booster coil to raise the brake pressure up to the limit of transferable brake torque. For HIL simulation, it is usually sufficient to "simulate" the solenoid by means of a resistance and to read in the booster control signal digitally as an input to the brake booster model.

Additional outputs of the VDC module include the VDC indicator, which tells the driver that active intervention is occurring or that the VDC is deactivated, and the four wheel speeds that are used, among other things, for interpolation of the GPS data by the navigation system (e.g., in tunnels).

CAN COMMUNICATION

In addition to actuators and sensors, the VDC system also needs to communicate with other ECUs in order to function properly. It mainly has to interact with the engine and transmission ECUs. Fig. 8 shows the most important data that is typically exchanged via the CAN bus.

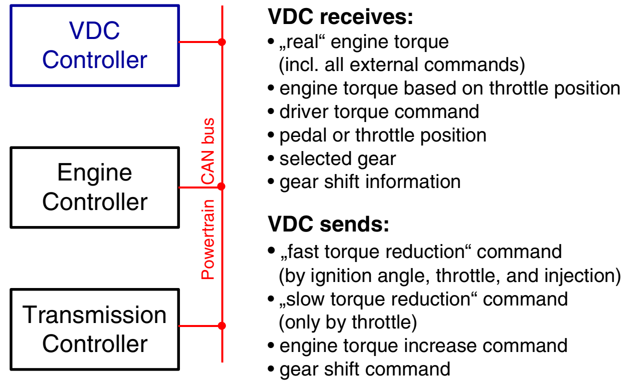

Figure 8: CAN communication of VDC with other ECUs [12].

For HIL simulation, this means that the behavior of the engine and transmission ECUs on the CAN bus has to be simulated (restbus simulation). In one direction, there has to be a suitable reaction to messages from the VDC module (e.g., with regard to torque reduction, see the chapter on Simplified ECU Software Models), and in the other, the engine and transmission messages have to be returned correctly to the VDC module (with regard to torque and gear shifts).

VEHICLE MODELING

MODEL COMPONENTS, TOOLS, AND REAL-TIME SIMULATION

As already described above, the models for HIL simulation have a particularly important role to play, as they have to represent the dynamics of a vehicle precise enough to close the control loops to the real ECU. To put it more precisely, all the sensor signals detailed above have to be computed consistently and in the correct physical relation to the corresponding actuator signals.

The basic model components are outlined briefly below. Implementation variants, the importance of submodels for the testing of ECUs, and modeling tools are also described in individual cases.

Powertrain Model

To test VDC systems, a simple look-up table based combustion engine with downstream elastic powertrain, including clutch, Trilok torque converter, manual or automatic transmission, differential transmission, and elastic drive shafts is needed. This powertrain must be configurable for different variants, e.g., for rear, front, or all-wheel drive (Fig. 9).

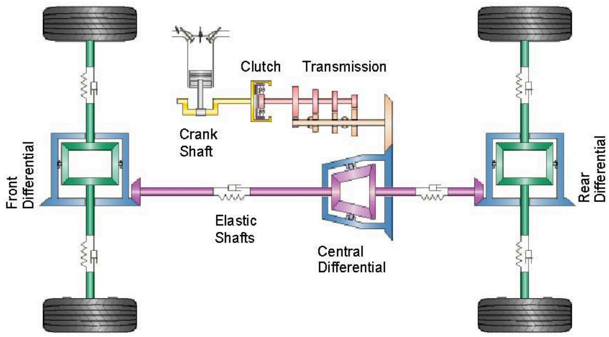

Figure 9: Powertrain model.

Vehicle Body Dynamics Model

Typically, the dynamics of a vehicle is described as a multi-body system which yields a set of differential equations of 2^{nd} order. For a simplified approach the necessary physical abstraction with 10 degrees of freedom (DoFs), 6 for the body translation/rotation and 4 for the wheels, is shown in Fig. 10.

Although multi-body simulation tools with C code export are available (e. g., SimPack [13]), the multi-body simulation codes/equations that are currently used are still mainly derived manually, or only partly automatically generated and then optimized for real-time processing. One reason is that there is often insufficient support for selecting suitable coordinate systems for flexible integration of different axle kinematics into the simulation code of the vehicle dynamics. Another more important reason why these modeling tools are not more widely used in HIL is probably inadequate code efficiency, i.e., processing times are too high.

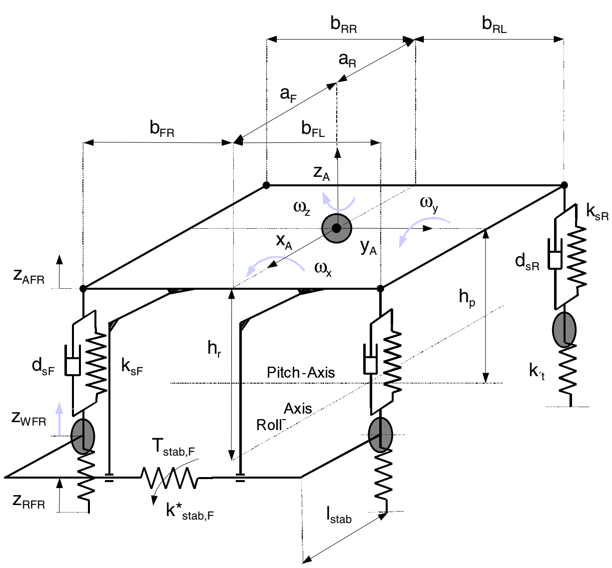

Figure 10: Body dynamics model.

End users of HIL systems are primarily concerned with testing an ECU. Thus, the user normally wants to apply a suitable real-time-capable model directly to achieve this objective instead of the prior (and possibly time-consuming) use of a modeling tool.

As HIL test technology becomes more widespread in the field of model-based design, e. g., in advanced engineering departments, modeling tools for HIL simulation are likely to grow in importance. Especially since the components being modeled in these areas are new mechatronic systems, and they are generally not available on the market as off-the-shelf models.

Axle Dynamics/Kinematics Model

Axles can be computed in real time either kinematically, using their geometric design data, or by tables. Axles based on geometry (e.g., rear axle semi-trailing arm, McPherson strut, four-bar axle) are more complex to model, but have the advantage of being easier to parameterize once all the design data is available. As this is frequently not the case, axles are nowadays often mapped as tables, which represent the toe-in, camber, and caster angles, and the position of the wheel hub as a function of the wheel lift, and additionally for steered axles, as a function of steering rod displacement. The table data is either captured at an axle test bench or computed by kinematics simulation (e.g., with MSC.Adams [14]). This kinematics simulation is used more frequently, since process integration or the automation of axle test benches are often insufficient. For example, typically steering angle effects can not be taken into account.

Tire Models

The tire model is extremely important to VDC interaction, as it describes all the governing forces and torques between the vehicle and the road surface according to the current wheel load. Finally, exactly these forces and torques are the control objectives of the VDC system.

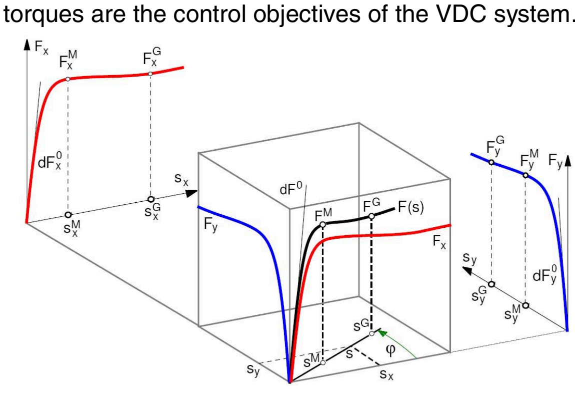

Figure 11: Easy-to-use tire model [15].

Some common tire models are the Easy-to-use Tire Model ([15], [16]) and the Magic Formula or Delft-Tire Model [17]. The latter is no doubt the most widely used, and all major tire manufacturers supply data sets for it. Both tire models include delayed, coupled longitudinal and lateral forces, self-aligning and bore torques. E. g. Fig. 11 shows the mutual dependencies of the longitudinal and the lateral forces within the Easy-to-use model.

Real-time implementation of these models is possible, but requires some effort, especially for starting from stand still, braking to stand still, and standing on an inclined road surface. Another aspect is the computation of the contact point or contact area, i.e., the interaction between the road surface and the tire. This topic will not be described in further detail here.

Steering Model

A model of the steering system is also indispensable for testing VDC systems. The model should take interventions by electric power-assisted steering (EPAS) into account. As the steering system is generally not the object under test, power-assisted steering can often be implemented by superimposing a speed-dependent steering force.

Brake Hydraulics Model

Unlike pure ABS systems, realistic testing of a VDC system requires a model of the brake hydraulics, as the system has to supply essential sensor variables (e.g., hydraulic pressure) in accordance with the control of the return pump, the pre-charge pump, and the solenoid valves (usually 12). It is mostly implemented by simple variable orifices (e.g., valves), which are coupled via hydraulic accumulators (e.g., wheel brake cylinders, damping chambers). An ESP 5.7 (see Fig. 12) from Bosch can be represented by five coupled, nonlinear differential equations of 1st-order, for each brake circuit. Effects such as hydraulic inductivity or cavitation are mostly ignored in HIL simulation.

If the structure of the hydraulic system changes frequently, or new types of hydraulic systems with as yet unknown modeling depths need to be examined, special modeling tools can be useful. Tools such as AMESim [18] and DSHplus [19] allow hydraulic systems to be modeled at component level and C-code for real-time simulation, e.g., in the form of a Simulink S-function, to be exported.

The particular effects that have to be included are on-off-controlled and continuously controlled valves in current use and valves with orifices with variable flow areas (change-over or pre-charge valve). These valves are often not available in common hydraulics libraries. Submodels for the shutdown delay of the return pump, which is used for VDC self-diagnostics, must be included also.

The brake hydraulics and the vehicle are coupled via the brake force at the wheels. As it interacts with the rest of the vehicle, the hydraulic system must be regarded as a stiff subsystem, whose numeric integration will be described in greater detail below.

As already mentioned in the introduction, when more detailed tests are required (e.g., when HIL is used for function development), it makes sense, and is quite usual, to construct a complete real brake hydraulic system.

This can then be operated in an environmental chamber, for flexible studies on temperature effects, which cannot yet be simulated with a reasonable effort.

The core model parts described so far can be constructed reasonably easily from submodel libraries available on the market (e. g. [20]). However, this is usually not sufficient for HIL simulation. To make the models realistic enough for the required maneuvers, additional items are needed: a driver model, a road model, and a maneuver control.

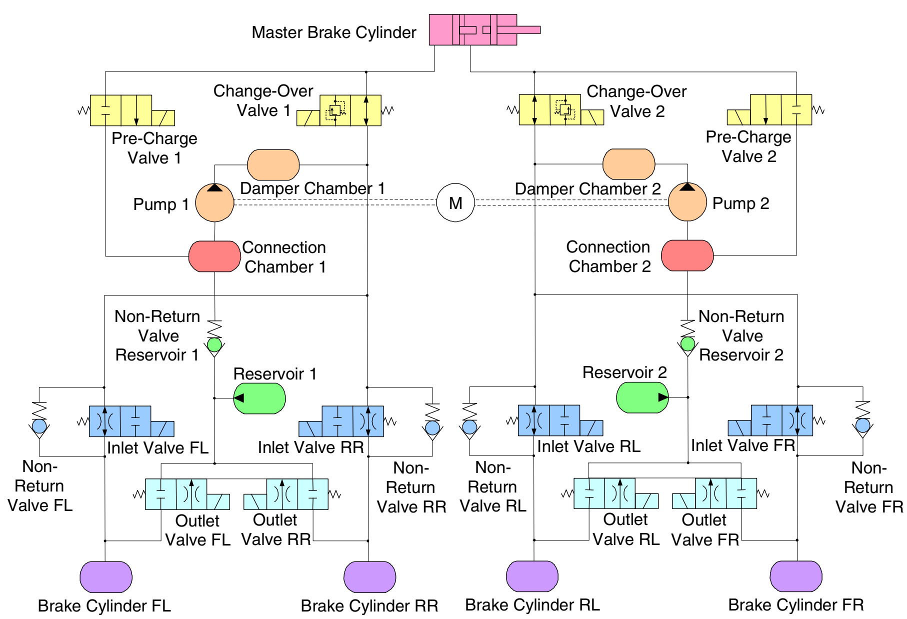

Figure 12: Brake hydraulics of ESP 5.7.

Driver Model

The driver model comprises a cycle driver (model-based controller) which is able to follow a specified speed profile, and a lateral controller, which guides the vehicle on the road via steering intervention. Optimum longitudinal speed adaptation also uses a road preview to ensure that lateral acceleration on the road stays within the permitted range. Some typical solution approaches to lateral control can be found in [21], [22], [23], [24], [25], [26], [27], [28], [29], and [30].

Cognitive driver models [31], [32] play only a minor role in actual HIL testing today. Driver models that optimize lap times in racing applications [33], or that map aggressive, sporty, or economical driver behavior in order to test adaptive transmission controls, could grow in importance in the future. New areas of applications will result in further challenges for driver models, e. g. for the test of Automatic Cruise Control (ACC) systems which require traffic flow simulation.

Road Description

Road models compute the longitudinal, lateral, and vertical profile of the road as inputs for the vehicle model and the driver. The interfaces between these submodels must be optimally adjusted to one another. The (horizontal) road profile is usually represented by straight, circular, clothoid, and spline segments. Each segment has friction coefficients, for example, and other surface properties (e.g. cross-groove profile and similar), which need to be entered conveniently via a graphical user interface [16]. Real time capable animation of the vehicle, road, and environment has also been a part of vehicle dynamics simulation in HIL for some years [34]. One important feature of good tool integration is therefore a road module that can generate a VRML representation of the road to avoid unnecessary manual work.

Data captured via GPS systems for specific test or racing tracks, or mountain passes, is also used for simulation, as an alternative to the road descriptions mentioned above.

Maneuver Control

Maneuver control basically comprises controls for the gas pedal, brakes, gear lever, and steering. Time histories captured in a vehicle are often fed in as stimuli to simulate test drives. Alternatively, it is usually possible to define these variables segment-wise over the time or over the traveled route. A distinction is usually made between longitudinal control (accelerate to 100 km/h at 70 % gas pedal, then brake with 60 % of the max. brake force, etc.) and lateral control (follow the road for 200 m or change the steering angle over time according to a specified steering angle table). Many experiments also require external or internal events to be included in the maneuver definition, e.g.: initiate braking if a specific speed or maximum lateral acceleration is reached, or if a specific CAN signal is sent by the ECU. Like the road description, consistency of these complex maneuver controls can be ensured only by a suitable graphical user interface.

Fig. 13 depicts the overall structure of a vehicle dynamics model with the needed components and their essential dependencies.

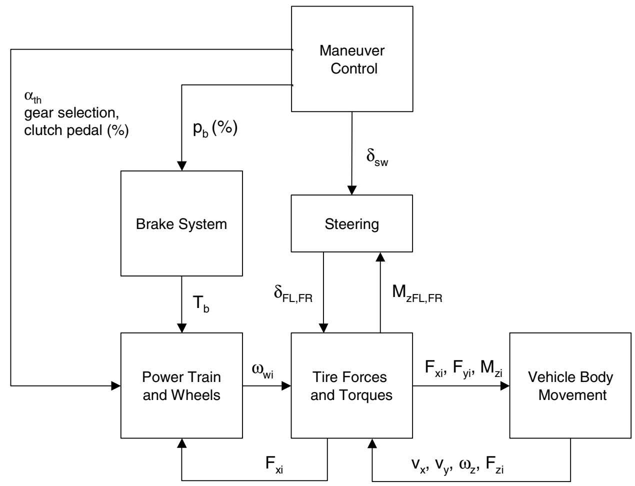

Figure 13: Vehicle dynamics model structure.

Simplified ECU Software Models

The last model components required are simplified models of ECUs or interfaces that are present in the real vehicle but typically not included in the simulator. To simulate the vehicle dynamics, for example, a starter model with appropriate starter control and a simplified control for the automatic transmission or Trilok torque converter is needed. In addition, the engine model needs an interface that carries out engine torque reduction as requested by the vehicle dynamics control via CAN (e. g., inverse engine map (LUT) with the engine speed ($\boldsymbol{n}_{mot}$) and desired torque ($\tau_{desired}$) as input and the throttle valve position as the output).

NUMERIC ASPECTS

Because the drive shafts are relatively stiff, modeling the elastic powertrain provides a so-called stiff differential equation system, i. e., there are relatively low eigenvalues up to approx. 10 Hz and eigenvalues over 100 Hz that do not easily allow stable integration of the differential equations by an explicit Euler method at the currently typical sampling rates of 0.5-1 ms.

Using e. g. a Runge-Kutta integration method instead of an Euler is also not generally more suitable for this type of model, because although they promise greater precision at the expense of longer processing times, they achieve that precision only if the state variables behave smoothly in the sampling interval. However, due to dry friction and gear shifts in the vehicle models, this cannot be assumed to be the case.

Numeric stability problems also occur in brake hydraulics modeling, due to low hydraulic volumes and high bulk modulus ($E_{Oil}/V \approx 13.000$ bar/cm^3). This list of stiff submodels continues, e. g., combustion engines (mean value models) with small intake manifold volumes (< 2 liters) which yield to numeric problems due to high manifold pressure gradients.

In the past, a number of solution strategies have been used to meet the real-time requirements. For example, in the case of brake hydraulics and the powertrain, the Jacobian ($\partial f(x)/\partial x^T$) of the system ($\dot{x} = f(x,u)$) can be computed analytically in advance to stabilize the Euler integration (pseudo-implied integration [15], [35]). This method necessitates the additional computation of the Jacobian matrix and is therefore always tied to a fixed model structure (at least for the subsystem under observation). If the structure changes, these terms must be recomputed.

Another way is to use an implicit Euler method, though the computational power required for the solution (zero search) rises if the state variables have steep gradients and this generally violates the real-time condition. This can be counteracted at the expense of precision by limiting the number of zero search iterations to a fixed value. Modeling tools like Dymola [36] are able to distinguish between fast and slow subsystems and to choose an implicit Euler integrator for the fast system parts and an explicit one for the slow parts [37], which can considerably reduce computing time, especially, if the fast subsystem requires only a small amount of computation compared to the slow parts.

As regards hydraulics simulation, [38] and others have shown that small hydraulics accumulators for coupling hydraulic subsystems can be avoided. This results in a differential algebraic equation system (differential equations with algebraic boundary conditions) whose differential parts can be integrated far more stably and faster because the high eigenvalues are no longer present. The algebraic boundary conditions must also be solved iteratively. Limiting the number of iterations despite a loss in precision can be a very stable, real time capable solution for specific subsystems. The disadvantage is that in a block diagram -based tool such as Simulink, the algebraic equations cannot be inserted and solved efficiently except by hand-written code.

Simulink therefore offers another option to cope with numerically stiff systems: system parts with high eigenvalues can be grouped in subsystems for multiple evaluation within one sampling step (FOR iterator block). If a local block for integration within these systems is implemented (1/s-block), stiff systems can be solved elegantly (e.g., with tenfold oversampling) without having to derive additional equations and without imposing serious restrictions on downstream block-based modeling. The effectiveness of this method basically depends on selecting a suitable oversampled subsystem. Like all the other methods, it results in a correspondingly higher, but deterministic, processing time.

USER INTERFACE

Simulation/Modeling Environment, Parameterization and Variant Handling

It is important to implement the model in an open environment like MATLAB/Simulink. This allows the user to extend the model by more complex ones (e. g. for network simulators) or even replace parts of the model. Users can add proprietary tire models or new axle kinematics models, or vary the powertrain by Haldex coupling or a Torsen differential, if the HIL model is completely open and accessible and not in the form of C or Fortran code.

In addition to the GUIs for road parameterization and maneuver control described above, more suitable GUIs are needed for parameterizing the model components (powertrain, axles, tires, etc.). To ensure convenient variant handling, an integrated GUI component must bring together all the handling controls for offline simulation and for real-time simulation independently of the modeling tool. This final point is extremely important, as vehicles with greatly varying configurations e. g., with regard to the powertrain (transmission variants, different tires, etc.) have to be tested with the same ECU. For future systems, it will also be important to have an automation interface (COM, DCOM) for such a tool, so that higher-level automation tools can set all the necessary structure and parameter variants.

Typical vehicle models in current HIL applications contain all the model components mentioned above. As a rough estimate, this results in approx. 24 mechanical degrees of freedom for the powertrain, body motion, steering, and wheels. In addition, there are 8 states for tire dynamics and 10 states for the brake hydraulics. In other words, there is a minimum of 66 states without the driver or (software) ECU models. Models of similar or even higher complexity (see veDYNA [16] and CarSim [39]) can be executed on a real-time system (e.g., dSPACE DS1006 with 2.2 GHz AMD Opteron™ Processor [34]) at 65 -200 µs, so processing time today is no longer a limiting factor to modeling depth. A real HIL application including standard I/O and CAN bus restbus simulation for a common VDC module can be calculated in less than 200 µs execution time. The challenges to modeling for HIL applications therefore lie more in model parameterization and validation. The parameterization problem can be resolved by suitably integrating data acquisition into the electronics development process. In the future, model validation using measurements from real vehicles could be automated by means of optimization methods.

The final point to be made about modeling is that (as so often) the “whole” is more than the sum of the parts. One consequence of this is that domain-specific modeling tools and individual model libraries for hydraulics or powertrain components have so far been used mainly in niches of HIL simulation. The majority of systems today are based on complete vehicle dynamics models with optimally coordinated submodel components and addi-

tional visualization, parameterization and operating software.

TYPICAL TESTS ON VDC SYSTEMS

For testing the vehicle dynamics several standard test maneuvers are defined which are used in track testing on proving grounds with real vehicles as well as in HIL simulation. These tests can be distinguished in

- open-loop procedures with constant, fixed or predefined steering wheel angle, brake and accelerator pedal and
- closed-loop procedures where a driver (or driver model) takes the road information into account to keep the vehicle on a predefined course.

Most of the test procedures have been standardized by the ISO technical committee ISO/TC 22/SC 9: Vehicle dynamics and road-holding ability [40]. Typical test procedures for ABS are e. g.:

- part-brake and full-brake tests: brake performance test to evaluate the brake distance for 100 to 0 km/h (or 60 to 0 mph) under high-µ and low-µ conditions,
- µ-Split braking, i. e. straight-ahead braking on surfaces with split coefficient of friction (ISO 14512).

For TCS (traction control systems) mainly the acceleration on a flat or on an inclined road are studied under low-µ or µ-split conditions.

Finally for VDC systems the following tests are performed:

- double lane change maneuver (ISO 3888-1),
- steady-state circular driving behavior (ISO 4138),
- lateral transient response test (step steering wheel input, ISO 7401),
- braking in a turn (ISO 7975),
- braking in a turn with µ-split, or
- rollover protection test: NHTSA Road-Edge Recovery Test ("fish hook test").

These procedures are used to validate the vehicle model (without any control systems) as well as to validate vehicle dynamics control algorithms.

An important requirement to a vehicle dynamics simulation environment is therefore to support these types of tests procedures, or it should at least support the engineer to define complex maneuvers by means of a library of suitable maneuver steps (please refer to the chapter on maneuver control).

The following plots show a comparison between in-vehicle measurements and the corresponding simulation results for two driving maneuvers in order to validate the models for lateral (step steering wheel input, Fig. 14) as well as for longitudinal (straight ahead braking with ABS, Fig. 15) dynamics.

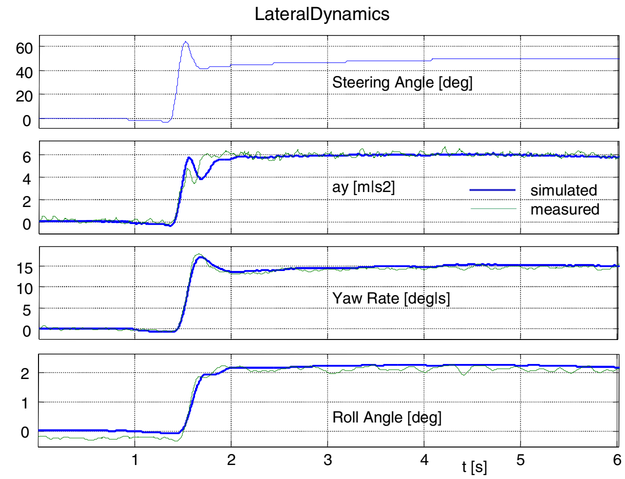

Fig. 14: Lateral step steering.

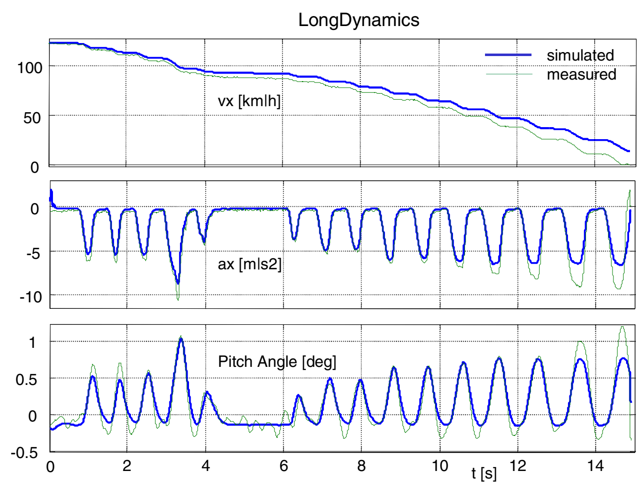

Figure 15: Longitudinal impulse brake.

In addition to testing the "normal behavior" of a vehicle, HIL simulation is also used to test the vehicle's behavior under faulty conditions, for example in cases where sensor or actuator failures occur. These tests can hardly be performed in real vehicles because it is difficult to set a specific error situation reproducible during driving. Additionally these test are dangerous for the test drivers and prototype vehicles can be destroyed as well.

APPLICATIONS

Application examples of HIL simulation for vehicle dynamics ECUs are presented below. The first is a typical simulator for testing *one* VDC module, the second for testing an ECU network. Special problems and possible solution approaches are also described.

SINGLE-ECU TEST SYSTEM FOR VDC MODULES

Fig. 16 shows a typical standard simulator of the kind frequently used in HIL tests on VDC systems. It consists of a simulator rack and valve current capture unit, on which the VDC module is fixed.

Figure 16: Typical mid-size simulator for HIL testing of single ECUs. Device under test: ContiTeves MK60.

At the bottom of the rack is a remote-controlled power supply unit that simulates the battery and allows the battery voltage to be varied from within the real-time simulation (undervoltage and overvoltage tests, voltage drops during engine start, etc.)

The real-time processor hardware and the I/O hardware can be seen above that. The processor hardware in this system is a DS1006 Processor Board, equipped with an AMD Opteron® Processor at 2.2 GHz. This board computes the model components for vehicle dynamics simulation as described further above, and the sensor and actuator scaling. To handle the simulator's inputs and outputs, a DS2211 HIL I/O Board is used (more information can be found in [41]). This is the standard board for dSPACE HIL applications. It provides, for example, the entire I/O for the simulation of a typical 8-cylinder engine, e.g., crankshaft angle synchronous signals; CAN communication; and analog, digital, and PWM I/O, including the necessary signal conditioning. However, the board is not restricted to engine applications, but is used in a large variety of different areas, particularly in testing vehicle dynamics ECUs. For example, it has a fast digital signal processor that provides signal generation in a range of microseconds and is used for purposes such as simulating active, intelligent wheel speed sensors (see Fig. 5).

The top part of the simulator rack shown in Fig. 16 contains a load and failure simulation unit. The load boards can accommodate small resistance loads, e.g., the substitute load for the brake booster solenoid or the RC circuit for simulating the return pump. The failure simulation boards are used to generate electrical failures (open wire, cross short circuits, and short circuits to battery voltage (Vbatt) or ground), especially for testing diagnostic functions in the ECU (OBD II). The load unit can also contain special signal conditioning modules, such as a current source/sink for the active wheel speed sensors. The real-time hardware (signal processor) drives the module by an analog output signal, which the current source/sink module converts to a proportional current signal (maximum 30 mA).

On the software side, the entire dynamic model and the complex I/O (incl. CAN messages, etc.) are completely specified in MATLAB®/Simulink®, and the real-time-capable model code and I/O code are generated automatically (Real-Time Workshop®). Extensive Simulink block libraries are available for defining the I/O (dSPACE Real-Time Interface, RTI). The generated code is linked and downloaded to the real-time hardware.

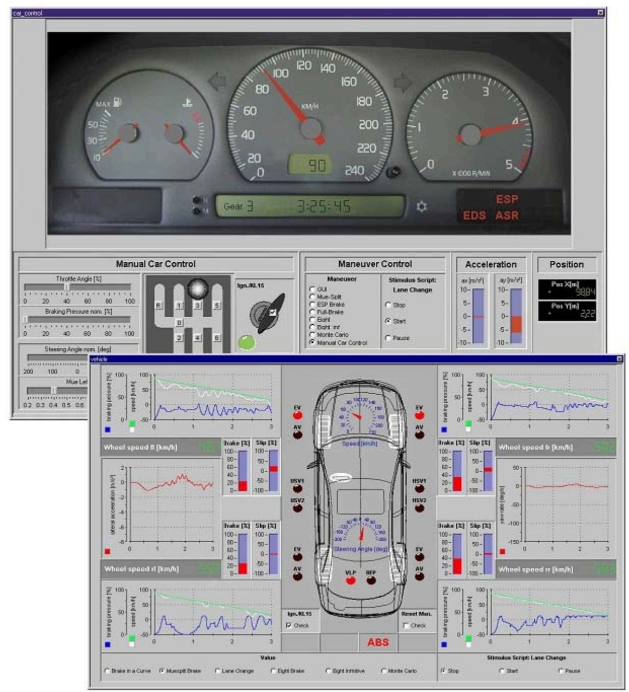

Figure 17: Layouts for instrumentation of the vehicle dynamics HIL experiment.

For experiment control, interactive operation, and instrumentation, ControlDesk [34] can be used. This provides online access to all real-time variables (parameters and outputs of all the blocks of the Simulink model). Fig. 17 shows two examples of application-specific layouts from the field of vehicle dynamics. If tests need to be performed automatically, AutomationDesk [42] is used. This provides project and test administration facilities, a graphical test editor, and test libraries for a great variety of different test scenarios.

To assess simulation results in vehicle dynamics, time histories need to be evaluated, and real-time, 3-D animation is also important. As with the model and I/O defini-

tions, development engineers should not have to worry about the implementation details of the animation, but be able to concentrate on the actual task of optimizing vehicle dynamics. Programs such as MotionDesk (Fig. 18) make this possible by providing a Simulink library for 3D transformations, which allows fast, simple conversion of coordinate systems (e.g., of wheel-specific or body-specific coordinate systems to the world coordinate system required for the animation). Animated force and torque vectors and the ability to record video sequences (AVI format) also make it easier to evaluate the results. An important criterion for a real-time animation tool is that the animated bodies (geometric data, number, environment information) must be completely decoupled from the actual animation program. If this is not the case, it is not possible to properly integrate any desired geometries without recompiling the animation tool.

Figure 18: MotionDesk for the animation of the vehicle motion

Fig. 19 shows HIL simulation results obtained from an experiment (ABS functionality during a full brake maneuver) performed with a HIL simulator as it has been described above. The unit under test was a Bosch ESP.

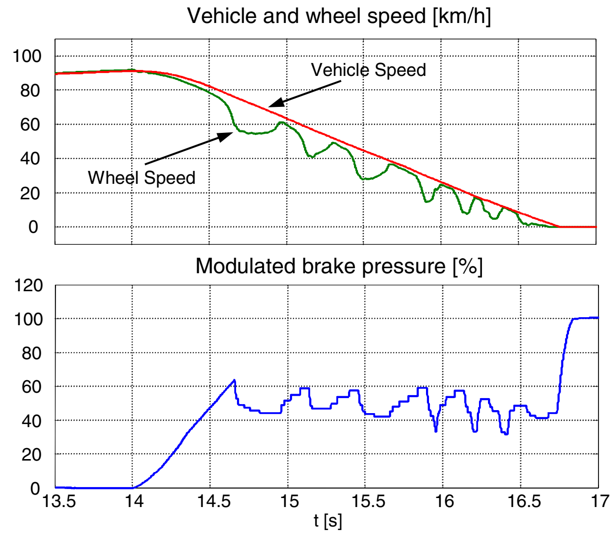

Figure 19: HIL simulation of a full brake maneuver with a real VDC system in-the-loop.

NETWORK TEST SYSTEMS (FULL-SIZE SIMULATOR FOR VDC MODULES)

As the number of ECUs installed rises, along with an increased level of networking and more sharing of sensors and actuators, test systems for vehicle dynamics control are also growing in complexity. While the tests run on individual ECUs are mainly hardware and function tests, network simulators are essentially used to test distributed functions and either the whole or parts of the CAN/LIN network.

The growing importance of testing ECU networks is also reflected in the growing number of publications on the subject [43]. Applications in powertrains and vehicle interiors at Opel [44], Audi ([1], [2]), DaimlerChrysler [45], Fiat/Elasis [46] and Ford [47] have been published, in addition to applications for racing vehicles [48], [49].

Fig. 20 shows an example of a network simulator for the powertrain and vehicle dynamics components of the Bugatti Veyron 16.4, a sports car with more than 1000 hp. Due to the low production numbers for this vehicle, only very few prototypes are available for ECU testing. Systematic use is therefore made of HIL technology [50]. The entire system is controlled interactively via ControlDesk, and 3-D animation of the driving behavior is visualized by MotionDesk.

Figure 20: HIL simulator for testing the ECU network of the Bugatti Veyron 16.4.

In addition to large systems for testing an entire ECU network with the HIL simulator, smaller test systems are also frequently used to run only the vehicle dynamics ECUs, or two to three closely networked ECUs, on the simulator. Depending on the vehicle project platform and the OEM's or supplier's organizational structure, there exist different requirements and test system configurations. Some typical combinations are VDC systems combined with CDC, EPB, and also ACC and electronic steering systems.

TEST OF VDC-RELATED SYSTEMS

Finally, some typical problems with VDC-related ECUs and corresponding solution components are presented below.

Electronic Parking Brake (EPB)

In new vehicles, the electronic parking brake is replacing the classic mechanical parking brake. The stationary vehicle is braked either by means of a central actuator which actuates the brake calipers via linkage or by means of local electrical actuators on the wheels (e. g., TRW). EPB systems frequently have an inclination sensor integrated into the ECU, which prevents the vehicle from rolling backwards when started on a slope (with manual transmission).

Direct stimulation of the inclination sensor is particularly problematic for HIL simulation. One solution is to place the ECU on a turnable platform that is controlled by the simulator (see Fig. 21). The platform is given the current vehicle inclination by the real-time simulation and inclines the ECUs accordingly.

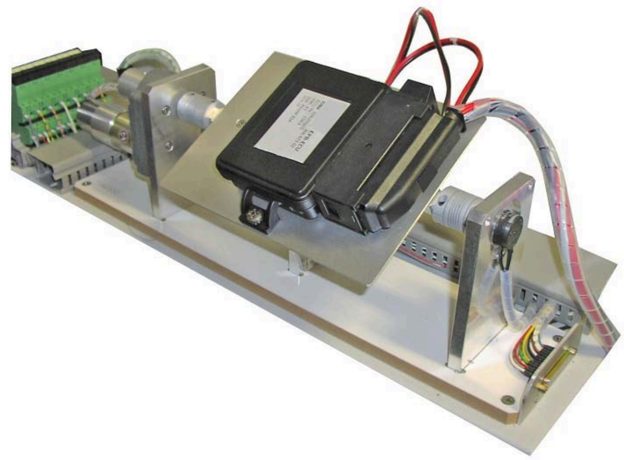

Figure 21: Turnable platform with mounted EPB ECU for stimulating an internal inclination sensor.

Due to the fact that a precise simulation, e. g. of the friction effects at the brake actuators, is very difficult, the brake forces are measured at the real brake calipers by means of force transducers. These forces are then used as inputs to the simulation model. Fig. 22 shows an EPB actuator that is mounted directly on the brake caliper, the force transducer replaces the real brake disk.

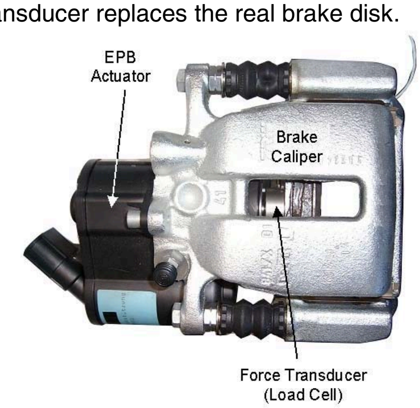

Figure 22: EPB actuator and measurement hardware for capturing the real forces.

Adaptive Cruise Control (ACC)

Common cruise control systems just keep the driver-selected set-speed. In addition to that, *adaptive* cruise control systems automatically adjust the vehicle speed to maintain a driver-selected distance from the vehicles ahead. Therefore, ACC systems are much more complex with respect to sensors and actuators. Typically, the systems use radar sensors (to detect vehicles ahead) and yaw and steering data (from the VDC system) to determine which other vehicles are in the vehicle's predicted path. A connection to the VDC system via CAN or via direct brake booster access is used to decelerate the vehicle.

For HIL simulation the radar sensor has to be simulated and a traffic flow simulation of a certain number of vehi-

cles is required. This model has to generate the horizontal angles as well as the relative speeds and absolute distances of all vehicles in the range of the radar sensor. This data has to be transferred to the ACC controller. Typically radar sensor and ACC controller are located in the same enclosure so that a special version of the ACC system with open radar sensor interface is used for HIL testing purposes. One example of such a system is the Bosch Puma ACC emulator with CAN interface to the radar sensor. As a result, radar sensor simulation by means of CAN message generation can be performed.

The ACC system communicates with various controllers via CAN, for example:

- with the engine controller to accelerate or decelerate (active torque intervention),
- with the brake system (ESP) to actively brake the vehicle and get information on the driving direction (yaw rate, steering angle and vehicle speed),
- with the restraint system (airbags, seat belt tensioner) if a crash situation is very likely or even unavoidable (pre crash system), and
- with the instrument cluster to display the status of the ACC system.

This communication has to be handled by the HIL simulator by transmitting and receiving CAN messages and reacting accordingly with real-time models of the ECUs involved in the scenarios. In order to achieve a more realistic behavior of these ECUs and their CAN communication it is also possible to connect the ECUs as *real* components to a vehicle dynamics network simulator (please refer to the chapter “Network Test Systems”).

The setup described above is usually sufficient for testing the ACC ECU as well as its CAN communication. But it is not possible to test the radar sensor itself, which is of course crucial for the overall system functionality. In order to test also the sensor in [51] a test facility called VEHIL is shown, in which the device under test can be a real vehicle with an ACC system. The car runs on a chassis dynamometer, while the vehicles of the surrounding traffic are simulated by special remote controlled autonomous vehicles. These so called moving bases get their input from a real-time traffic simulation.

<u>Electrical Steering Systems</u>

Basically two types of systems can be distinguished in this field:

The first ones are electrical power steering (EPS) systems. Instead of a hydraulic system the steering is supported by forces/torques that are generated electrically. The major advantages of this type of system are, that a complex hydraulics is not needed anymore and that it is very flexible with regard to the adaptation to different driving situations but also to different vehicles (packaging).

The second ones get their power still from a conventional hydraulics but a steering angle can be superimposed to the driver’s steering input by an electrical system which is e. g. combined with a planetary gear. These systems (e. g. BMW AFS) can be used to stabilize the vehicle dynamics in critical driving situations.

Depending on the desired test scenarios three different interface levels between the EPS system and a HIL test bench can be identified:

- An interface on the signal level (Fig. 23, interface 1) is adequate, if the focus lies on software tests. It is often used by the suppliers of EPS systems, because for them it is easy to make the internal signals of the ECU accessible. Of course in such a setup a sophisticated actuator model (motor, transmission etc.) has to be provided to obtain the precise motor currents in dependency of the measured PWM signal, that is normally given to the power stages. Moreover, torque and position sensor signals have to be synthesized.

- If the power stages should also be tested, but the actuation system is not available as a real component, the test system must have a dynamic high current sink/source (≥ 80 Amps), which is controlled by the real-time system according to the simulated motor (Fig. 23, interface 2). In this case the modeling effort is still high, but the mechanical demands are as low as for interface level 1.

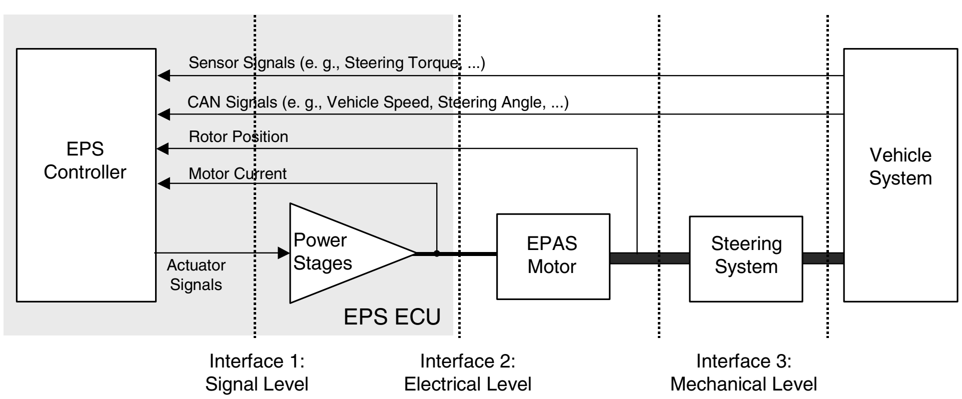

Figure 23: Typical architecture of EPAS systems and possible interfaces to HIL test benches.

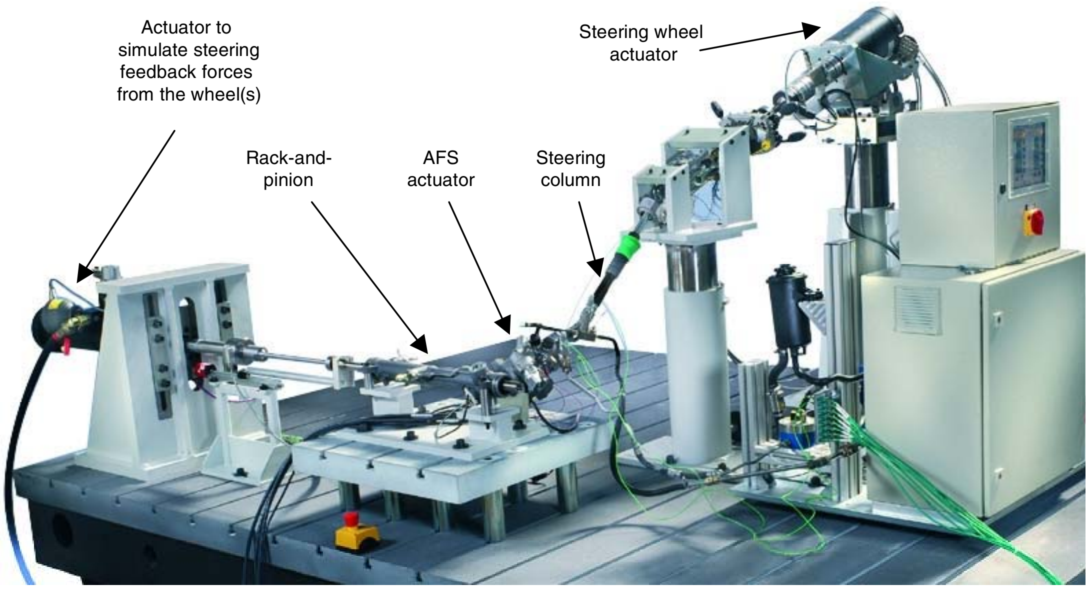

Figure 24: HIL test bench for Active Front Steering (BMW AFS [52], [53])

- On the interface level 3 (Fig. 23) the entire EPS system including the motor and maybe even the transmission are built up as real parts. In opposite to the scenarios above, no model of the steering system is needed here. But of course an electrical or hydraulic actuator system will be necessary to put an actual load on the steering wheel and on the rack or directly on the pinion. This means that the software efforts for modeling are replaced by a higher hardware effort (see Fig. 24). Such an approach makes sense especially if a suitable model can not be obtained or if the actuator system should undergo e. g. durability tests.

FURTHER DEVELOPMENTS AND OUTLOOK

The development departments of many OEMs and tier1 suppliers are currently working on further improvements to yaw rate control. They are combining the ESP/VDC with one or more other active steering or chassis systems, such as Active Front Steering (AFS), Electronic Power Steering (EPS), Continuous Damping Control (CDC), Active Body Control (ABC), Air Suspension System (ASS), Active Torque Control (X-Drive, BMW [54]) and Anti-Roll Control (ARC). These systems have names such as Integrated Chassis Control (ICC, OPEL [55]), Vehicle Dynamics Management (VDM, Bosch [56]), and Global Chassis Control (GCC, Continental Teves [57]), and consist of a super ordinate, coordinating software layer that generates reference values for the underlying control systems in such a way that positive control interferences are reinforced (e.g., yaw rate stabilization for shortening braking distances by >15 % in an ESP/AFS combination) and negative interference is suppressed by stricter separation of working areas. Global safety concepts and switch-off concepts can also be implemented.

It is in the nature of these systems that they mainly operate at critical vehicle dynamics limits and in safety-critical situations, which makes HIL simulation particularly useful for them. Network simulators similar to those used for powertrains and body electronics, made up of the HIL simulators available for lower-level subsystems, will be used more commonly in the future.

Current developments make it clear that the networkability of HIL simulators, their flexibility with regard to variant handling, their fast adaptability to new and additional ECUs, and their test automation abilities will become increasingly important for handling the complexity of the electronics in this field.

LITERATURE:

[1] Gehring, J.; Schütte, H.: Automated Test of ECUs in a Hardware-in-the-Loop Test Bench for the Validation of Complex ECU Networks. Society of Automotive Engineers, SAE Paper No. 2002-01-0801.

[2] James, A.; Rudolph, M.; Gehring, J.; Pöhlmann, T.: Hardware-in-the-Loop bei Audi-Antriebssträngen. ATZ 4/2002.

[3] Bach, Th.: Real-time Simulation in Anti-lock Brake System Development based on a Personal Computer. VDI 6th International Congress "Measurement and Testing Techniques in the Automotive Industry", Berlin, April 28, 1992.

[4] Hanselmann, H.: Advances in Desktop Hardware-in-the-Loop Simulation. SAE Paper 970932, 1997.

[5] Bach, Th.; Schmitt, H; Schwanke, W; Tumbrink, H.-J.: ROADRUNNER Real-time simulation in anti-lock system development. SAE paper No. 950758.

[6] Kiffmeier, U.; Otterbach R.; Schütte H.: Real-Time Simulation of a 3-D Vehicle Dynamics Model on the DEC Alpha Processor. 15th IMACS World Congress '97, Berlin, August 24-29, 1997.

[7] Krohm, H.; Gheorghiu, V.: Hardware-in-the-Loop Simulation for an Electronic Clutch Management System. SAE paper No. 950420.

[8] Grund, C.; Schineis, W.: A Hardware-in-the-Loop Test Bench for Wheel Slip Systems. ISATA `97, Florence, June 16-19, 1997, Paper No. 97VR022, June 1997.

[9] Bosch: Automotive Handbook 5th Edition. Robert Bosch GmbH, Stuttgart, 2000.

[10] Zanten, A. T. van; Erhardt, R; Pfaff, G; Kost, F; Hartmann, U; Ehret, T.: Control Aspects of the BOSCH-VDC. AVEC `96, Intern. Symposium on Advanced Vehicle Control, Aachen, June 24-28, 1996.

[11] Michalsky, Th.; Büdenbender, M.: Testing Transmission ECUs With Integrated Sensors. Auto Technology, Volume No. 1, pp. 62-65, June 2001.

[12] van Zanten, A.: Fahrdynamik & Fahrdynamik-regelsysteme (Vehicle Dynamics and Vehicle Dynamics Control Systems). IIR Training Seminar, Düsseldorf, Germany, 2004.

[13] SimPack: See product information on http://www.simpack.com/

[14] ADAMS: See product information on http://www.mscsoftware.com/products/products_detail.cfm?PI=413

[15] Rill, G.: Simulation von Kraftfahrzeugen. Vieweg Verlag, Braunschweig, 1994.

[16] veDYNA User's Guide, Tesis DYNAware, Munich, 2001, (http://www.tesis.de).

[17] Pacejka, H.-B.: Tire and Vehicle Dynamics. SAE, Warrendale, PA, 2002.

[18] AMESim: See product information on http://www.amesim.com/

[19] DSHplus: See product information on http://www.fluidon.de/

[20] TNO ADVANCE: See product information on http://www.automotive.tno.nl/VD/Docs/Brochure_advance.pdf

[21] Sharp, R. S.; Casanova, D.; Symonds, P.: A Mathematical Model for Driver Steering Control, with Design, Tuning and Performance Results. Vehicle System Dynamics, 33 (2000), pp. 289-326, 2000.

[22] MacAdam, Ch. C.: Application of an Optimal Preview Control for Simulation of Closed-Loop Automobile Driving. IEEE Transactions on Systems, Man and Cybernetics, Vol. SMC-11, No. 6, June 1981.

[23] MacAdam, Ch.: The MSC Driver Model. Chapter 7, 1980.

[24] Wolter, Th.-M: Ein hybrides Modell zur Kraftfahrzeugführung. ZMMS Spektrum Band 14, Fortschritt-Berichte VDI, Reihe 22, Nr. 9, VDI Verlag, Düsseldorf, 2002.

[25] Vögel, M.: Fahrbahnmodellierung und Kursregelung für ein echtzeitfähiges Fahrdynamikprogramm. Diplomarbeit, TU München, 1997.

[26] Majjad, R.: Hybride Modellierung und Identifikation eines Fahrer-Fahrzeug Systems. Dissertation Universität Karlsruhe, 1997.

[27] Kiencke, U.; Nielsen, L.: Automotive Control Systems, For Engine, Driveline, and Vehicle. Springer Verlag, Berlin Heidelberg New York, 2002.

[28] Butz, T.; Ehmann, M.; Stryk, O. v.; Wolter, Th.-M.: Realistische Straßenmodellierung für die Fahrdynamiksimulation in Echtzeit. ATZ, Heft 106 (2004), pp. 118–125, February 2004.

[29] Riedel, A; Wurster, U: Fahrermodelle in der Praxis. Automotive Engineering Partners, March, 1998.

[30] Prokop, G.: Modeling Human Vehicle Driving by Model Predictive Online Optimization. Vehicle System Dynamics 2001, Vol. 35, No. 1, pp. 19-53, 2001.

[31] Jürgensohn, Th: Hybride Fahrermodelle. ZMMS Spektrum Band 4, Pro Universitate Verlag, Sinzheim, 1997.

[32] Irmscher, M: Modellierung und Simulation von Motivationseinflüssen auf das Fahrerverhalten. ZMMS Spektrum, Band 12, Fortschritt-Berichte VDI, Reihe 22, Nr. 6, VDI Verlag, Düsseldorf, 2001.

[33] Ehmann, M.; Butz, T.: Raceline Optimization and Driver Modeling for the Simulation of Race Car Dynamics in Real-Time. Race.Tech 2004 Conference, Munich, Oct. 14-15, 2004.

[34] dSPACE MotionDesk, dSPACE ControlDesk, dSPACE Simulator. See product information on http://www.dspace.de/

[35] Rill, G.: A modified implicit Euler Algorithm for Solving Vehicle Dynamic Equations. EUROMECH, Halle, March 1 – 4, 2004.

[36] Dymola: See product information on http://www.dynasim.com/.

[37] Schiela, A.; Olsson, H.: Mixed-mode Integration for Real-time Simulation. Modelica Workshop 2000 Proceedings, pp. 69-75, October 23-24, 2000.

[38] Borchsenius, F.: Simulation ölhydraulischer Systeme. Fortschritt-Bericht VDI, Reihe 8, Nr. 1005, VDI Verlag, Düsseldorf, 2003.

[39] CarSim Product Description, Mechanical Simulation Corporation (MSC), Ann Arbor, MI, 2001. (http://www.carsim.com/).

[40] ISO technical committee ISO/TC 22/SC 9: Vehicle dynamics and road-holding ability http://www.iso.org/iso/en/CatalogueListPage.CatalogueList?COMMID=847

[41] Schütte, H.; Plöger, M.; Diekstall, K.; Wältermann, P.; Michalsky, Th.: Testsystems in the ECU Development Process. ATZ/MTZ Special Issue, Automotive Electronics, pp. 16-21, March, 2001.

[42] Lamberg, K.; Richert, J.; Rasche, R.: A New Environment for Integrated Development and Management of ECU Tests. Society of Automotive Engineers, SAE Paper No. 2003-01-1024.

[43] Wältermann, P.; Schütte, H.; Diekstall, K.: Hardware-in-the-Loop Test verteilter Kfz-Elektroniksysteme (Hardware-in-the-Loop Testing of Distributed Electronic Systems). ATZ 05/2004, pp. 416-425.

[44] Köhl, S.; Lemp, D.; Plöger, M.; Otterbach, R.: Steuergeräte-Verbundtests mittels Hardware-in-the-Loop-Simulation (ECU Network Testing by Means of HIL Simulation). ATZ 10/2003, S. 948.

[45] Honisch, A.; Hutter, A.; Schmid, H.: Vollautomatisierter Test von Steuergeräte-Netzwerken (Fully Automated Test of ECU Networks). ATZ/MTZ Special Issue, Mercedes-Benz A-Klasse, pp. 116-125, October, 2004.

[46] Plöger, M.; Ferrara, F. et al: Testing Networked ECUs in a Virtual Car Environment. SAE Paper No. 2004-01-1724.

[47] Heiming, B; Haupt, H.: Hardware-in-the-Loop Testing of Networked Electronics at Ford. SAE Paper No. 2005-01-1658.

[48] Waeltermann, P.; Michalsky, T. Held, J.: Hardware-in-the-Loop Testing in Racing Applications. SAE Motorsports Conference 2004, Dearborn, Mi, USA, SAE Paper No. 2004-01-3502.

[49] Urban, P.; Wältermann, P.; Henking, B.: Toyota Motorsport Racing Ahead with dSPACE (In German: Toyota Motorsport mit dSPACE auf der Überholspur. Automotive Engineering Partners 6/2001, pp. 40ff. English Version available via: http://www.dspace.de/ftp/papers/dspace_AutEP_0111_e_f22.pdf.

[50] Baeker, W.; Lichtenthäler, D.: Bugatti: Powerful Cars Need Powerful Tests. dSPACE News 01/2004, dSPACE GmbH, Paderborn (www.dspace.de).

[51] TNO VeHIL: Vehicle Hardware-in-the-Loop-Test-Facility. http://www.automotive.tno.nl/smartsite.dws?id=57.

[52] Abou-El-Ela, A.; Wachinger, M.; Krenn, M.: HIL Test Bench for BMW's Active Steering. dSPACE News 03/2004, pp.14-16.

[53] IABG: Intelligent Testing. Brochure. IABG Ottobrunn, Germany (www.iabg.de).

[54] Fischer, G.; Pfau, W.; Braun, H.-S.; Billig, C.: xDrive, Der neue Allradantrieb im BMW X3 und BMW X5. ATZ 2/2004, pp. 92-102.

[55] Holzmann, H.; Hahn, K.-M.: Application of HiL-Simulation in the Development Process of Modern Chassis Control Systems Considering Integrated Chassis Control (ICC). VDI-Bericht Nr. 1828, pp. 549-558, Steuerung und Regelung von Fahrzeugen und Motoren – AUTOREG 2004.

[56] Trächtler, A.: Integrated Vehicle Control Using Active Brake, Steering, and Suspension Systems. VDI-Bericht Nr. 1828, pp. 463-473, Steuerung und Regelung von Fahrzeugen und Motoren – AUTOREG 2004.

[57] Schwarz, R.; Rieth, P.: Global Chassis Control – Systemvernetzung im Fahrwerk (Global Chassis Control – Integration of Chassis Systems). at-Automatisierungstechnik, 7/2003, pp. 300-312.

ABBREVIATIONS

ABC: Active body control
ABS: Anti-lock braking system
ACC: Adaptive cruise control
AFS: Active front steering
BAS: Brake assist system
CAN: Controller area network
CDC: Continuous damping control
DoF: Degrees of freedom
DSP: Digital signal processor
ECU: Electronic control unit
EPAS: Electric power-assisted steering
EPB: Electronic parking brake
ESP: Electronic stability program
EPS: Electric power steering
GPS: Global positioning system
HIL: Hardware-in-the-Loop
ICC: Integrated chassis control
ISO: International Organization for Standardization
LIN: Local interconnect network
LUT: Look-up table
NHTSA: National Highway Traffic Safety Administration
OBD II: Onboard diagnostics 2nd generation
PWM: Pulse width modulation
TCS: Traction control system
VDC: Vehicle dynamics control
VSD: Valve signal detection unit

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