Hardware-in-the-Loop:
The Technology for Testing Electronic Controls in Vehicle Engineering

Dr. Peter Waeltermann
dSPACE Inc.
50131 Pontiac Trail Wixom,
MI 48393-2020 USA
Tel. +1 (248) 295-4700
Abstract

Hardware-in-the-loop simulation (HIL) is an integral component in the electronic development process for testing control functions. HIL simulation involves operating mechatronic systems, particularly electronic control units (ECUs), in a closed loop with components that are simulated in real time to test them intensively in this virtual environment. This paper provides an introduction to the subject of HIL simulation. First, the essential hardware and software components will be presented, including the dynamic models. Then, the most important HIL applications will be described, such as the engine, vehicle dynamics, and electric drives. This paper will also take a look at network simulators (testing ECU networks) and some special solutions.

Key Words
mechatronics, hardware-in-the-loop, simulation, automotive technology, vehicle electronics

1 Introduction
The importance of electronics and software has grown considerably in all areas of everyday life over the last several years. This trend can clearly be seen in mechanical engineering (mechatronics), as well as in automotive, aerospace, commercial & off-highway vehicles, electric drives, medical engineering, robotics, and home entertainment, where today’s smart phones, televisions and games consoles have more computing power than the Apollo rockets 45 years ago.

Virtually all innovations in the field of automotive engineering are now based on new or further developed electronics. This applies to the latest engine technologies such as start-stop and hybrid drives, as well as passive and active safety systems (airbags, ESP, pre-crash), driver assistance systems (ACC, lane keeping systems, night vision), and infotainment systems.

Today’s top-of-the-range cars include up to 100 ECUs that are connected with one another via various bus systems. The ECUs communicate with each other, and participate in vehicle-to-vehicle and vehicle-to-infrastructure (V2X) communications. The complexity of this networked structure of functions, combined with an enormous number of different vehicle versions and variants (different engines and transmissions, different options, country-specific versions, etc.), is a major challenge in terms of developing and testing vehicle ECUs.

Hence, intensive work is currently being done to define manufacturer-independent standards for function modules and architectures, with the goal of separating the hardware, the operating system, and the application layers (AUTOSAR, JASPAR, etc.). Hardware-in-the-Loop technology (HIL) has become an integral part of the electronics development process of vehicle manufacturers and suppliers for testing single ECUs, as well as ECU networks. This technology is described in detail below.

1.1 Definition and Context
Hardware-in-the-Loop simulation is a method used in the product development cycle in which one or more real components interact with components that are simulated in real time (dynamic models).

The part of the system that is not simulated can consist of real devices, machines, or mechanical test benches. Nowadays, however, the term is mainly used to refer to a real system that consists of one or more ECUs, controllers, or intelligent mechatronic components for which a virtual environment is simulated electrically and dynamically.

The interactions between the real and the simulated subsystems make tough real-time demands on the lat-
The simulated subsystem has to perform the following actions within one simulation step:

- Read in the measurement signals (actuator control by the ECU)
- Calculate and perform numeric integration (simulate the entire dynamic model of a real system)
- Output the results (sensor simulation for the ECU).

The result is a closed loop between the real controller and the simulated plant. Failure to meet real-time conditions can result in unstable simulation and even damage to the real technical device.

Figure 2 shows a signal flow that illustrates this structure. In the real system, the real ECU is integrated in the real vehicle (left); in HIL simulation, it is connected to the HIL simulator via electrical interfaces (center and right).

1.2 Importance and Benefits, Requirements

The major aims of HIL simulation are to enhance product quality, to master complexity, and to reduce development costs. This last aim is achieved by moving function tests and diagnostics tests from tests drives or test bench experiments to the HIL laboratory. The result is that the number of expensive prototype vehicles and time spent at the test bench are considerably reduced. HIL tests can be reproduced as often as required and also automated. It is now common practice to completely automatically run, evaluate, and document tests overnight or on weekends. This allows the test operators to concentrate on assessing tests, implementing new tests or test scripts, and adjusting tests that failed (for example, due to ECU errors). Automation provides far greater test coverage than manual tests, and this enhances quality and maturity.

Frequently, HIL simulators are also used to perform tests that would not be possible at all on a real system (for example, because no prototype vehicles are available yet), or that would be critical for the components (danger of damaging or destroying prototypes) or even dangerous for the test driver (for example, if there is a sensor error at top speed on a sharp bend).

Thus, HIL simulation makes it possible to give an ECU an environment that is so realistic that the ECU’s diagnostics system does not detect any inconsistencies in the electrical signal quality or the dynamic behavior of the plant (no fault memory entry by the diagnostics). In this situation, any tests that would typically be performed in or with the vehicle (or on a test bench) can also be performed on the HIL simulator. This is the basis for inducing error situations intentionally. Diagnostic functions (with short circuits, functional faults or communication errors), fail-safe levels and limp-home mode can be tested in this way.

1.3 Structure of the Paper

The next section of this paper begins by presenting the essential hardware
and software components of HIL systems, including the dynamic models. Then a few HIL applications will be described in detail, such as test systems for the engine, vehicle dynamics, and electric drives. Then we will take a look at network simulators (testing ECU networks) and a few special solutions.

2 HIL Systems: Basics and Components
HIL systems can vary considerably from application to application. Even so, it is possible to identify numerous components that are always present in a similar form. These are shown for a single ECU in figure 3 and explained in greater detail in the following chapters (see [SPD+01] and [WR06]).

2.1 Hardware Components of the HIL System
Host PC: An off-the-shelf Windows® PC is generally used as the user interface to the real-time processor (experiment software) and for executing the modeling and implementation software (see section 2.2.1). To ensure high data rates and low latencies in communication with the real-time hardware, specially optimized inter-face cards are used, and sometimes also Gigabit Ethernet.

Real-time processor system: Standard server PCs with a real-time operating system have now almost caught up with special real-time processor boards in terms of pure processor performance, which is particularly important for model calculation. However, connection to the I/O cards is problematic, as server PCs are frequently not optimized for this. Thus, processor boards with optimized I/O interfaces are used for high-end applications to achieve an optimum overall system consisting of a processor and I/O.

I/O boards and signal conditioning: HIL applications for vehicles require boards for simple analog and digital signals, and also special boards for fast, engine-angle-synchronous signals (see section 3.1.1) for fast sensor simulation (wheel speeds, knock signals) or actuator measurement. Some of these I/O boards already possess the necessary protection circuits and signal adaptations to specific electrical system voltages (12 V, 24 V, 48 V, etc.); otherwise, separate signal conditioning is used (e.g. for current interfaces, lambda probes, etc.).

Bus systems: The ECUs form networks and communicate via various bus systems in the vehicle (CAN, LIN, FlexRay, MOST). When parts of the network are operated in HIL, the bus behavior of all the missing ECUs has to be appropriately simulated. Thus, the HIL simulator must be able to generate messages (this is called restbus simulation) and to read all the messages coming from the ECU. Here too, special I/O boards are used, frequently with intelligent subprocessors or FPGAs and suitable bus transceivers.

Electrical loads and load simulation: ECUs control electrical actuators (called loads), e.g. valves, electric motors, relays, current-controlled actuators and piezo injectors. Either the real loads or electrically equivalent circuits can be used in an HIL system. The ECU's diagnostic system monitors these actuators so that it can take appropriate action if a fault occurs (short circuit, open circuit) or at least inform the driver. Quite often, it is sufficient to connect a substitute resistance to the ECU as a load. However, if the load itself has dynamic behavior (variable resistance such as in a headlamp) and the ECU performs diagnostics on this, either a real load is integrated into the HIL system or an electronic (=...
dynamic) load simulation controlled by the real-time system is used.

**Electrical fault simulation:** To generate the electrical fault states mentioned above, failure simulation units are often integrated into the HIL system. These can simulate hard short circuits and open circuits, and also leakage resistance and loose contacts. Relays or semiconductor switches are used for this depending on requirements. The failure system is programmed and activated either interactively or via test automation.

**Real components:** To treat ECUs realistically, real components are often necessary. These might be loads that are not easy to simulate, or that can only be simulated with a lot of effort, and sometimes smaller setups or even complex test benches (see section 3.3) are used.

**Power supply:** Simulating the vehicle electrical system and the battery vehicle also requires power supplies whose voltages can be specified dynamically by the simulator. This is especially important for undervoltage and overvoltage tests (e.g., in jumpstarts by trucks) and for simulating voltage drops when starting the engine.

### 2.2 Software Components of the HIL System

The software components for an HIL system are subdivided into the operating software (PC), the real-time software (real-time system) and the dynamic plant model.

#### 2.2.1 Operating Software (Implementation and Experiment Software)

Graphical programming of control functions using simulation environments like MATLAB®/Simulink® is established as a quasi-standard for function development. It is also, therefore, natural to use this environment to describe dynamic behavior of the plant. In lack of standards for exchanging models among various simulation tools, Simulink S-function was the proven method. However, now with FMI standards, the exchange of dynamic plant models is much more feasible for HIL simulation. As plant dynamics sub-models are combined a configuration environment is necessary to help with connection of signals, definition of tasks, interrupt handling, IO hardware connections, and auto-generation and compiling of code.

Interactive operation of the HIL system requires configurable GUIs with a wide range of different views (figure 5), which can be adapted flexibly to specific projects. In addition, 3-D visualization is in-
dispensable, especially for vehicle dynamics applications, as complex driving maneuvers cannot be suitably evaluated by recorded time behaviors alone. However, the greatest benefit is derived from HIL systems if test runs are not interactive but automated. HIL tests frequently run overnight or on weekends, and all that the operators need to do during the day is to examine the generated test reports, repeat failed tests, and implement new tests. The time saved by automation means that when used systematically, HIL systems pay for themselves in only a short time, typically less than a year.

Script languages such as VBA, MATLAB and Python are frequently used for automation. However, there are also test tools on the market that allow test implementation to be performed in graphical form (figure 6). As in Simulink, the test creator can put together a test from single test steps or whole test sequences from libraries, and “program” parallel as well as serial test sequences.

2.2.2 Real-Time Software
To meet HIL simulation’s tough real-time requirements, real-time operating systems (or operating system kernels) designed for maximum I/O throughput and minimum I/O latency are used. Multitasking, multi-rate simulation (different step sizes within the model) and multiprocessor systems must also be supported. These requirements are often fulfilled only by special real-time kernels. However, it is now also possible to set up simple HIL systems based on standard real-time operating systems such as QNX and LINUX-RT.

2.2.3 Dynamic Models
To close the control loop between the ECU and simulator inputs/outputs, dynamic plant models are needed. These must provide a sufficiently good representation of the system to be controlled. The model quality must be so good that the ECU does not detect any inconsistencies or implausibility. The real-time capability of the model is another decisive criterion for HIL use. Very detailed models (including FEM approaches and 3-D flow simulation) are often used in engine and chassis development, and such models are far from being real-time-capable. For HIL operation, therefore, specific models and model approaches are often used that are real-time-capable and sufficiently precise with regard to the ECUs’ sensors.
**Combustion models:** With engine simulators, mean value models are often used. These are usually generic and are parameterized by means of test bench measurements made for the specific engine. Static internal engine relationships are frequently approximated by using look-up tables. Either the engine models are operated in test bench mode (the engine speed is held constant by means of a simulated load machine) or drive cycles are run via a drivetrain model (e.g. EUDC, FTP75). For an overview of engine models, refer to [SWS07]. Development work recently started on engines with in-cylinder pressure measurements, and this has made greater model precision necessary for HIL operation. Models that describe inlet and outlet behavior and combustion very precisely are therefore being used more and more. However, these models are far more complex to parameterize and also require smaller step sizes (typically 100 µs) [SWS07]. Another current major development issue is the suitable simulation of the exhaust system with a particulate filter, an oxidation catalytic converter or even selective catalytic reduction (SCR).

**Vehicle dynamics models:** ESP ECUs are very safety-critical systems. Sensor signals are therefore monitored very precisely (e.g. by defined initialization sequences for each single sensor) and checked for plausibility toward one another by means such as internal observer models. This results in tough demands on vehicle dynamics models. In HIL systems for vehicle dynamics control systems (ASB, ESP), the essential masses (vehicle body and wheel mass) are simulated, and the wheel suspensions (interaction between the body and wheel) are represented by multidimensional look-up tables.

**Environment models:** As well as the actual vehicle models, virtual test
drives also require environment models such as a driver model, a road description and a maneuver control (figure 7). All these components have now become standard in commercial vehicle dynamics models. An overview of vehicle dynamics HIL systems is provided in [SW05]. At the moment, driver assistance systems (ACC, lane change/lane keeping/parking assistants, environment detection, etc.) are an important focus in the development of automotive and commercial vehicle electronics. Not only models of the main vehicle are required for these, but also models of the environment, in other words traffic simulation that appropriately simulates the behavior of other vehicles and the signals from radar sensors, ultrasonic sensors, and cameras, and feeds them to the ECUs.

Other development issues include all kinds of electric drives and their peripherals (vehicle electrical system, battery systems, DC-DC converters, etc.).

3 HIL Application Areas
HIL systems are employed for testing single ECUs (see section 3.1) and ECU networks. Single ECUs are frequently tested thoroughly by their suppliers before they are delivered to the vehicle maker - the original equipment manufacturer (OEM) - for integration. The OEM then performs comprehensive network tests on all the ECUs together (see section 3.2). Some special solutions involving test bench integration are described at the end of this chapter.

3.1 Testing Single ECUs
This section pays particular attention to engine and vehicle dynamics ECUs and ECUs for electric drives used in hybrid vehicles, electric steering systems, etc. It is not possible to cover all the details in this article, so references to the relevant literature are provided.

3.1.1 Combustion Engine ECUs
ECUs for combustion engines generally have time-based and crank-angle-based functions and subsystems. The main task of engine control consists in high-precision\(^2\) capture of the engine angle (reading crankshaft and camshaft signals) and the output of injection and ignition signals. While the ECU’s normal I/O can be simulated sufficiently well with a typical sampling rate of 1 ms, special fast subsystems are used for the crankshaft-synchronous signals (figure 8). As already mentioned in section 2.2.3, engine ECUs make very high demands on the models. All the sensor signals for these must have good representations in the model, because otherwise the ECU goes into fail-safe mode, or it is even impossible to start the engine in the simulation. For detailed information on engine simulations and engine models, please refer to [HP07].

3.1.2 Vehicle Dynamics ECUs
Electronic stability program (ESP) perform selective braking on single wheels to ensure that the slip angle is reduced, thereby stabilizing the vehicle in critical driving situations such as wet or icy roads. The driver’s intention is detected by means of the steering wheel angle. Sensors for the yaw rate (rotation around the vertical axis), lateral acceleration and wheel speed are used to determine the vehicle’s motion. In addition, relevant variables are estimated by means of an internal vehicle model (observer) [WR06]. An ESP is a safety-critical system. Sensors and actuators are monitored very precisely (by initialization and plausibility checks), so (for example) active,
intelligent wheel speed sensors with disturbance-proof current interfaces are used. ESP test systems have to fulfill the requirements on signal type (current sources and sinks for the wheel speed, suitable valve signal detection, etc.) and on model quality very precisely. Figure 9 shows the basic structure of the HIL control loop and explains the interactions. For further information, please refer to [SW05].

### 3.1.3 Electric Drives and Hybrid Vehicles

Electrical drives are becoming more and more important in modern vehicles, whether they are in the drive train (e.g. hybrid drives) or in the area of the chassis and the steering system. For example, in conventional power steering, the pump is driven continuously by the combustion engine via a belt or a chain, while an electric steering pump needs energy only when it actually has to support steering. The basic structure of an electrical machine in a vehicle is shown in figure 10. The controller itself, with its current controller, sends pulse-width-modulated control signals to the power stages, which then switch the real voltages and currents for the electric motor. This generates torques on a vehicle component via mechanical shafts. For control, motor currents and the motor position are usually returned. A basic difference between electric machines and other vehicle components is that the machine is controlled at a very high clock rate (typ. 10-20 KHz). This makes high demands on the HIL simulation. I/O sampling rates in the millisecond range and mean value models, which are used for combustion engines, are not sufficient for fast current and position control. Special FPGA-based hardware is needed for this. Figure 11 shows a generic FPGA board that can be equipped with application-specific modules, e.g. for measuring the PWM control signal or for simulating incremental encoders or resolvers (clock rate 40 MHz). Moreover, small model parts can be simulated directly on the FPGA to achieve simulation step sizes in the sub-μs range.
Figure 10 shows the possible interfaces between an HIL system and the electrical machine’s ECU. Depending on the application and the modeling depth, the interfaces can be defined and implemented either on the mechanical level (e.g. with mechanical load motors), on the electrical power level (by means of electronic load simulation), or on the signal level (without relevant power). HIL solutions for all these cases have been published and are available on the market [WSW+07].

3.2 Testing the ECU Network
The vehicle manufacturers are responsible for the vehicle as an overall system, and for ensuring that ECUs from different suppliers work together. Thus, network testing on all the ECUs is of major importance in vehicle development. Figure 13 shows a typical ECU network with different buses and gateway ECUs [WSD04].

Among the buses implemented in vehicles, the CAN bus continues to be predominant. However, the less expensive serial LIN bus is frequently used for simple tasks, while FlexRay (chassis area) and MOST (infotainment) are preferred for high-speed applications. Additionally, different versions of Automotive Ethernet are becoming more and more important for new vehicle generations.

The objective of network tests on an HIL system is often to verify multi-ECU functions and bus communication, e.g. drivetrain coordination; the central locking system; the light and indicator control; or even the entire operating actions taken by the driver. Other tests cover network management: If the interior ECUs are not needed for some time, they have to switch to stand-by mode to reduce current consumption. If this does not happen, the battery goes flat, and after a lengthy stationary period it is impossible to open or start the vehicle. Thus, measuring sleep mode current is a very important part of HIL testing, and special current measurement boards in the μA range are used for this. Another problem in testing an ECU network is the large number of vehicle variants. The number of possible vehicle model variants and country variants for one platform is now so large that only a fraction of vehicle variants are available as genuine prototypes. The network HIL simulator makes it possible to switch ECUs in and out very quickly by means of test automation, so reconfiguration from one variant to another can take just a few seconds. This increases test depth and ensures that the ECUs reach a higher maturity at an earlier stage.
3.3 Special HIL Solutions

3.3.1 Integrated Sensors and Actuators

As already shown in figure 2, there is generally an electrical interface between the ECU and the (simulated) actuators and sensors. In this case the wiring harness can simply be opened up and connected to the simulator. However, if the ECU has integrated sensors or actuators, the interfaces between the ECU and the HIL system are at different locations (see figure 15).

Integrated sensors and actuators are frequently used in transmission ECUs that are installed directly in the automatic transmission. For HIL simulation, the integrated sensors must be stimulated physically, e.g. inductive speed sensors are stimulated by controlled coils, pressure membranes by strong lifting magnets, and temperature sensors by controlled hot plates.

ESP ECUs also require special measurement equipment, as the coils for controlling the twelve ESP valves are housed in the same enclosure as the ESP controller, so only the effect of the control (i.e. the magnetic field) can be captured by Hall sensors (see the valve signal detection on the left of figure 9).

The stimulation of internal sensors can even mean that to stimulate internal acceleration and yaw rate sensors, the entire ESP ECU, including valve signal detection, has to be mounted on a rotatable 3-D motion platform that is connected with the actual HIL simulator via a multichannel slip ring system (figure 16) [FPS09].

Figure 15: Integrated sensors and actuators: electrical interfaces are replaced by physical interfaces [LW00].

Figure 16: 3-D motion platform with ESP ECU and valve signal detection unit for stimulating integrated acceleration and yaw rate sensors.
For some users, it is important to test an entire mechatronic subsystem such as a steering system or a chassis on the HIL simulator in addition to performing pure electronics tests. Thus, fatigue tests have to be performed in addition to function testing. Classic mechanical test benches are coupled with HIL simulators for this. Figure 17 shows such a test bench for a steering system. Test benches have also been coupled for testing a part of the drivetrain; for example, a real Formula One transmission was connected to a simulated engine and a simulated drivetrain. The coupling of HIL simulation with mechanical axle test benches for function development and verification for active chassis has also been published.

4 Summary
This paper provides an overview of hardware-in-the-loop technology. The different HIL components were presented and some application fields from automotive engineering were described. Although the examples largely come from the field of passenger vehicles, it should be added that HIL is also widely used in the commercial vehicle and construction equipment industries, as well as in motor racing. Outside automotive engineering, HIL is being employed successfully in aerospace and defense, in ship engineering and in industrial automation.

There are many topics that could only be mentioned briefly in this article, or which had to be left out completely, such as driver assistance systems, as well as test methods and processes. These are described in detail in the reference literature (especially [S08] and [WR06]).

Literature


For more literature please see www.dspaceinc.com/go/hil-literature


Dr. Peter Waeltermann has a Master’s degree (Dipl.-Ing.) in Mechanical Engineering / Mechatronics and a Dr.-Ing. (Ph.D.) degree from the University of Paderborn, Germany. He worked with dSPACE GmbH in Paderborn, Germany, since 1999, where he held different management positions in the area of hardware-in-the-loop (HIL) simulation and project engineering. In the summer of 2014, he moved to dSPACE Inc. (USA) to take over a position as Business Director. On October 1, 2014, Peter became the President of dSPACE Inc.