Hardware-in-the-Loop Testing of Networked Electronics at Ford

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ABSTRACT

The number of electrical and electronic components in modern vehicles is constantly growing. Increasingly, functionalities are being distributed across several electronic control units (ECUs). While suppliers themselves are responsible for ensuring that individual ECUs function properly, only the OEM can test distributed functions. Moreover, with the volume of testing steadily growing, automated sequences are absolutely essential.

To test electronic networks in the vehicle, Ford Europe is using platform-based hardware-in-the-loop simulation with integrated failure insertion. The company is setting up a uniform, project-independent procedure, from standardized test definition to automated test sequences on a virtual vehicle, right through to structured evaluation.

INTRODUCTION

One of the standard tools for electronics testing, which has been widely used for years, is hardware-in-the-loop technology. Using this method, ECU manufacturers eliminate many errors during the project and development phases of the single ECUs.

While ECU suppliers themselves are responsible for ensuring that individual ECUs function properly, only the OEM can test distributed functions. Errors in ECU-networks with distributed functions cannot be detected without performing tests at the integration and function levels. This means that the complete system of networked ECUs must be tested. Here too, HIL simulation is a suitable tool for minimizing the volume of testing and automating tests to run them in a minimum of time.

The controller system of the Focus C-Max platform is an example of such a modern ECU network, Figure 1.

The ECU network of the Focus has a high-speed CAN bus (continuous) for the powertrain area and a mid-speed CAN (dashed) for comfort and multimedia. The standard equipment of the C-Max is marked yellow for the powertrain (PCM, HEC) and blue for the comfort area (PJB, RCM). All other modules are optional extras. The individual ECUs are as follows:

ABS Antilock Brake System (ABS/ESP)
ACU Audio Control Unit (incl. LowLevelNAV)
CDDJ CD-Changer
DDCU Driver Door Control Unit
DISP Display
EATC Electronic Automatic Temperature Control
EHAPAS El. Hydraulic Power Assist Steering
EPB Electric Park Brake
FACM Fuel Additive Control Module
FFH Fuel Fired Heater
HCM Headlamp Control Module
HEC Hybrid Electronic Cluster
KVM Keyless Electronic Cluster
NAV Navigation Module
PAM  Parking Aid Module
PCM  Powertrain Control Module
PDCU  Passenger Door Control Unit
PJB  Passenger Junction Box (GEM)
RCM  Restraints Control Module
RLDCU  Rear Left Door Control Unit
RRDCU  Rear Right Door Control Unit
RSE  Rear Seat Entertainment
SAS  Steering Angle Sensor
TCM  Transmission Control Module
VRM  Voice Recognition Module
YAW  Yaw rate/Lat Acc sensor cluster

TASKS OF THE SYSTEM

At Ford, tests on ECU network functionality are divided into three phases:

1. **Acceptance tests** on the individual ECUs’ low-level functionality
2. **Integration tests** on the individual ECU’s behavior in the network
3. **Functional tests** in the ECU network

Acceptance tests address the following issues:

- Was CAN communication correctly implemented by the ECU supplier?
- Is the CAN controller's bit timing correct?
- Are the specifications for ISO/OSI layer 1 and 2 complied with?

Integration tests focus on the following aspects:

- Is the CAN gateway functionality correctly implemented?
- Do all the ECUs enter sleep modes as specified?
- Is the current consumption of the ECU network within the specified ranges?
- Is the bus load correct?
- Do the on-board diagnostics work as required?

Function tests come at the end of the test chain with focus on the following:

- Do the ECUs make their sensor signals available to other ECUs via the CAN bus quickly enough?
- How fast do actuators, driven by their ECUs, react to demands from other ECUs via CAN?
- Are distributed and concentrated functions, such as power lock, power window lifter or airbag functions, performed correctly?

The specification of all these tests must take into account the following general requirements:

- Platform independence
- Variant independence
- Test equipment independence
- Reproducibility of tests
- Minimum assembly effort

As a consequence, the test system must meet extensive requirements:

- All pertinent ECU power drivers and signal outputs must be read in by the test system. It must be possible to capture the signals and store them in files if required.
- The test system must be able to stimulate all the ECU inputs.
- From the ECU’s point of view, the test system must behave like a real car. This requires closed-loop connections of the ECUs inputs and outputs with real-time capable models of all controlled systems, especially for the engine, transmission, vehicle dynamics and some of the body/comfort components.
- Real electrical fault insertion capability is required on ECU outputs in order to verify how the ECUs react to the insertion of known faults. For ECU inputs, electrical faults can often be stimulated by software.
- To test single ECUs, there has to be a convenient way of separating them from the network and setting them up to run in stand-alone mode.
- To investigate the behavior of the CAN networks, the test system must be able to perform the following tasks:
  - Trace and record data from all of the CAN lines simultaneously, with time stamps
  - Send predefined messages interactively
  - Generate triggers on start of frame for detailed analysis
  - Measure the time elapsed between a certain message with identifier “x” and a message with identifier “y”
  - Simulate the messages received and transmitted by nonexistent nodes and react to external triggers (events) or to events on CAN lines
  - Suppress all messages sent by one or more ECU
  - Modify specific signals inside CAN
- Generate hardware errors on the bus (e.g., by inserting additional capacitors or resistors between the CAN lines, generating error frames, destroying messages at arbitrary bit positions)
- It must be possible to verify network management functionality: sleep mode, alive mode, wake-up mode.
- Diagnostic access and remote control of diagnostic tools must be possible.
- For manual interactive operation of the system, the experiment software must be powerful and flexible, but also easy to use. The ability to automate the overall test system is crucial. A well-structured automation concept is essential, especially when functions need to be used on different platforms.
- The system must cover all the available, market-specific variants. There must be a simple way of activating the variants, if possible without changing the hardware set-up.
- For future developments the system must be easy expandable and reconfigurable.

**SYSTEM STRUCTURE**

With conventional test methods on test benches tests are performed manually, so they are not fully reproducible. Another drawback of conventional tests is the lack of possibility of automatic testing and report generation. Finally, on the static bench it is not possible to have complete test coverage because some plausible conditions are not simulated, especially for powertrain and chassis systems.

This is why Ford Europe is using platform-based hardware-in-the-loop simulation with integrated failure insertion to test electronic networks in the vehicle. The system hardware and software is provided by dSPACE. Ford has set up Virtual Vehicles at several locations, supporting different vehicle platforms. A viable concept for implementing the existing test specifications was developed in a joint project.

**HARDWARE OVERVIEW**

The core of the Virtual Vehicle for the Focus C-Max is a dSPACE Simulator Full-Size. It consists of four 19” cabinets, Figure 2. The ECUs were arranged according to their CAN bus membership and their functions. Cabinets 1 to 3 contain the ECUs of the high-speed CAN, with cabinet 1 serving the powertrain ECUs (engines, transmission) and cabinet 3 the chassis ECUs (ESP, EPB, EHPAS etc.). Cabinet 2 is used to hold all the high-speed CAN ECUs and their special measurement recording and positioning equipment. All the ECUs in the mid-speed CAN are assigned to cabinet 4. The ECUs themselves are installed in a separate frame (lab vehicle), which mimics a real vehicle and also accommodates most of the loads. The design of the mid-speed bus can therefore replicate that in the real vehicle. Cabinet 3 also holds the common power supply (battery simulation) for the entire vehicle.

This setup provides optimum access to the single ECUs and real loads, which greatly simplifies the replacement of individual components. Besides both parts of the Virtual Vehicle (Mid-Speed ECUs and High-Speed ECUs) can be operated completely independent.

![Figure 2: Simulator hardware of the Virtual Vehicle](image-url)
Each of the Full-Size cabinets is constructed similarly and contains:

- The high-speed, real-time processors for calculating the dynamic models
- I/O cards for acquisition and generation of discrete signals, boards for receiving and transmitting CAN messages
- The multiple modular signal conditioning components
- Failure Insertion Units (FIU) and load boards to make real or simulated loads available on ECU outputs and generate electrical faults.

The host PC is used both to develop models and to configure and run the experiment and the test automation software. The PC contains a CANcardX® for accessing the CAN busses for particular purposes like providing bus statistics and for diagnostic services.

The following list of input and output channels used in the Focus C-Max Virtual Vehicle clearly demonstrates the complexity of the system:

- 89 ADC channels
- 54 DAC channels
- 377 channels for digital I/O
- 12 resistor simulation channels
- 55 PWM input channels
- 20 PWM output channels
- Further special channels for ignition and injection measurement, crank and cam signal generation, wheel speed signal generation, knock signal generation
- 4 different CAN controllers, two for each CAN network, for providing gateway and fault simulation in the Simulator
- Extra CAN controllers for diagnostic functionalities

The total number of ECU pins connected to the test system is about 620.

The bird’s eye view in Figure 3 gives an impression of the whole system including dSPACE Simulator Full-Size, lab vehicle for body/comfort ECUs and host PC.

Figure 4 shows the networking of the real-time processors that compute the models of the controlled system and the I/O scaling. The relevant I/O hardware is assigned to each processor. The master node is in the chassis rack. The vehicle model is completely computed on the master node. The directly adjacent slave processors serve the high-speed CAN network: chassis I/O (Slave A), the transmission models and transmission I/O (Slave B), the engine models and engine I/O (Slave C). Slave C also provides the high-speed CAN gateway and communication with Slave D, which serves the entire mid-speed CAN ECU network and its I/O.

SOFTWARE OVERVIEW

Simulation Model

The vehicle model was built in Simulink® according to NPA Vehicle Model Architecture (VMA). This is Ford's in-house standard for supporting model-based vehicle system engineering activities. It contains a model framework as well as signal conventions, bus structure conventions, and naming conventions [3].
The VMA framework is defined by a highly modular top-level subsystem of the vehicle, including the signal connections between these subsystems. Figure 5 shows the VMA structure of the Virtual Vehicle, which is adapted for optimum interprocessor communication in the multiprocessor system. The submodels for the individual processors are marked in color.

The top-level subsystems are:

- Driver (Drv)
- Environment (Env)
- Electrical Systems (Ele)
- Body / Comfort
- Powerplant (Pwp)
- Transmission (Trn)
- Vehicle

Within the Vehicle subsystem the functionality is divided into:

- Driveline (Dln)
- Chassis (Cha)
- Brakes (Bra)
- Steering (Ste)
- Vehicle Stability Control (Vsc)
- HIL specific I/O (HIL)

This modular approach to the model of the controlled system and its I/O connections allows flexible adaptation to different vehicle platforms and vehicle variants within an HIL system, and also improves portability to other HIL systems. When the Virtual Vehicle was constructed, it was possible to use models of the controlled system and controllers from several HIL test systems at Ford for single ECUs in the powertrain. The standardized interfaces between the modules and the standardized names used in the signal busses meant that only minimal modifications were needed to integrate the complex models of diesel and gasoline engines, the chassis, and ESP functionality.

The VMA model of the Virtual Vehicle contains comprehensive models of the controlled system in each of the top-level subsystems. In the powertrain, the veDYNA vehicle model from TESIS in Munich, Germany, was coupled to Ford’s own engine models via a separate transmission model. For body/comfort functionalities several smaller, independent submodels are implemented. Examples are climate control, wipers, and door locks.

Figure 5: Top level of the Simulink® simulation model
Experiment Software

The entire graphical user interface for manual operation is implemented with dSPACE ControlDesk. Many well-structured layouts, partly with photorealistic visualizations, enable the user to interact with the system and manage the real-time experiments.

![Figure 6: Photorealistic experimentation layout for operating the car control functions](image)

Especially for testing vehicle dynamic functions it was decided to integrate the 3-D online animation tool MotionDesk. It enables the movement of the car to be visualized in a virtual world.

Automation Software

Although it is possible to perform many tests manually, the full benefit is reaped only when automation is introduced.

Test automation leads to broader test coverage and a greater test depth. It allows tests to be repeated at a high rate and reproduced easily. Test automation means optimum utilization of the HIL system.

In connection with the introduction of HIL simulation for function integration, Ford is setting up a uniform, project-independent test procedure, from standardized test definition to automated test sequences on a virtual vehicle, right through to structured evaluation.

Test specifications and rules are being defined for all test phases, from acceptance tests for single ECUs to integration tests on ECUs in the network and right through to network function tests.

The entire test strategy is transferred to the Virtual Vehicle. The core of the automation software is AutomationDesk, dSPACE’s test tool based on graphical programming. It has the following advantages over the pure Python approaches:

- The integrated test project management enables the user to store and manage tests, test data, test results and test reports in one place. This facilitates close integration into the development process.
- The library concept consists of global built-in libraries for basic functionality, global custom libraries for extensions to the automation functionality, and project-specific libraries. Test components and tests can therefore be reused easily and conveniently.
- Result management and report generation guarantee test reproducibility, data security, and consistency.

![Figure 7: View of dSPACE’s test automation tool AutomationDesk with a test sequence](image)

APPROPRIATES TO TEST AUTOMATION

To cover the entire test specification, the Virtual Vehicle was equipped with HIL-specific hardware and software features. A major objective was to make modification work between individual test tasks as easy as possible. The system structure adaptations necessary for switching between acceptance, integration, and function testing should be largely automatic and capable of integration into the tests.

The following section describes the problems that arise when tests are performed automatically, and how the Virtual Vehicle solves these problems.

ACCEPTANCE TESTS

Acceptance tests are always performed when new ECU hardware, new ECU software, or new CAN communication specifications are available. The tests are performed individually on each ECU.

- The ECU specifications are tested at the physical and data link levels on the relevant bus channels: bit timing, voltage ranges, rise times.
- The test volume is approx. 20 tests per ECU.
Acceptance tests are performed relatively frequently during vehicle development. Automation removes the need to perform repetitive, routine tasks.

**Problem:** Each ECU must be tested without influence of the other ECUs in the network. Special termination resistors must be set. Bit timing and signal rise times on CAN have to be measured with high accuracy.

**Solution:** CAN gateway

The Virtual Vehicle is equipped with a gateway for all CAN busses, Figure 8. This makes it possible to separate individual ECUs from the network and switch in special terminating resistors. The behavior of the physical layers and the data link layer can therefore be captured for each ECU individually.

![Figure 8: CAN gateway functionality in hardware and software](image)

**INTEGRATION TESTS**

Integration tests are performed in the real CAN bus structure. The parameters to be verified include bus loads, sleep/wake-up capability, message priorities. Current consumption (airport tests) and gateway functionality between the high-speed and the mid-speed CAN are also tested. Integration test automation has very different requirements regarding the test system than acceptance test automation.

**Problem:** The network behaviour must be observed without influence by the test system.

**Solution:** The Philips TJA1041 CAN transceiver

In the Virtual Vehicle a special sleep mode-capable CAN controller monitors all messages on the bus. This controller is also able to listen without influencing the bus and it is sleep mode-capable itself. The controller can be directly addressed in the VMA model via a special Simulink® library.

**Problem:** For measuring the current consumption of an ECU in work mode and also in sleep mode a special current measurement strategy is necessary.

**Solution:** Power Switch Module

The Power Switch Module main purposes is switching the supply voltage for ECUs and unidirectional high side current measuring. It provides five current measurement ranges from 1.25 mA to 50 A. Range switching is done automatically so that ECU sleep mode and referring current consumption can be distinguished from normal operating mode behaviour. The power switch module provides high precision measurement of power consumption in mA range (< 2% @ 1.25 mA). The module can be configured and controlled using a separate CAN bus. The Virtual Vehicle allows the current consumption of any desired ECU groups or single ECUs to be measured, simply by switching the supply lines.

**FUNCTIONAL TESTS**

In general functional tests comprise the whole vehicle functionality. The focus with Virtual Vehicle is testing of distributed functions with communication on high-speed or mid-speed CAN. Examples are airbag tests, door locking functions, window lifter, etc. This also has specific requirements regarding the test system.

**Problem:** Vehicle behavior must be mimicked as plausibly as possible in order to verify these functions.

**Solution:** HIL I/O board for engine simulation

Special HIL boards (DS2210 HIL I/O Board) are used for the engine control units. These have a large number of standard I/O channels for sensor simulation and actuator measurement, and also special functions for generating and reading crank-angle-based signals with high accuracy and convenience.

**Problem:** Some ECUs are equipped with internal actuators and sensors which must be measured or stimulated by the HIL system.

**Solution 1:** Valve current capture for ESP Controller

Since this ECU drives the hydraulic valves via integrated coils, the adaptation system is necessary for sensing the magnetic field of the coils by Hall sensors, Figure 9.
Solution 2: Inclination positioning for electric park brake controller (EPB)

Normally ECUs for electric park brakes have an internal inclination sensor to control automatic park brake release. This sensor can not be simulated by the HIL system.

For simulating the inclination and stimulating the integrated inclination sensor the ECU is mounted on a rocker that can be controlled via the real-time application, Figure 10.

Problem: In distributed functions information is transmitted from one ECU to another. The reaction of involved ECUs on communication errors must be investigated.

Solution: CAN gateway

The existing CAN gateway used for separating single ECUs in acceptance tests, can also be used for the functional tests, to suppress messages or corrupt their contents, Figure 8. Figure 11 shows the gateway functionality of a CAN channel, which was implemented in Simulink®. The signals of the message received by the CAN controller 1 on the left are passed on to the controller 2 on the right following signal manipulation.
Problem: To develop just one vehicle, functional tests have to be performed for different country and vehicle variants, with a minimum of assembly effort.

Solution: Variant handling

The term variant handling covers a combination of different measures carried out in the software to automatically adapt the structure and parameterization of the controlled system models, and of the resulting real-time application, to the test conditions of each specific structure. The VMA structure provides optimum conditions for this. Switching between variants is mainly done via libraries, by configuring and enabling subsystems and parameter files.

AUTOMATION CONCEPT

In the field of functional testing, tests on individual functions can be very extensive. Different tests also repeatedly require similar actions, for example, using the ignition key or other operating elements, and evaluating engine control processes.

For this reason, hierarchical library was set up for creating and running tests, in accordance with the general requirements of system, program, and variant independence. The library consists of custom library modules (CL), which are organized in individual function areas (F). Underneath these are the individual serials (Ser). The term serial refers to a closed, parameterizable control flow.

The automation concept of the Virtual Vehicle contains two custom libraries: Base Library and Functional Tests. The Base Library contains serials with generic subfunctions. For example, there is an operating function, parameterizable for different vehicle variants, for each operating element. Evaluation modules for actuator signals were also implemented. Figure 12 shows an excerpt from the CL Base Library as an example.

The Base Library was designed so that the individual serials cover functions on different Ford platforms. This ensures easy portation to other HIL systems and reuse in future development projects.

The second CL, Functional Tests, contains serials that describe the actual tests. 80% of each test consists of serials from the Base Library. The tests are also parameterizable and not restricted to use in the Virtual Vehicle. Figure 13 shows an excerpt from the CL Base Library as an example. Figure 14 shows the specification for one particular test serial. Serials coming from the Base Library are marked.
Because the functional tests were implemented as serials, they can be combined as required to form sequences for execution. The sequences are the actual executables in the automation project. They not only cover test execution, but also provide result management and report generation.

![Figure 14: Definition of a serial for the functional test door locking](image)

CONCLUSION
The ever-increasing complexity of electronic systems in modern vehicles and the rising portion of distributed functions requires new ways of developing and testing ECUs. After a discussion of the questions arising when networked ECUs are to be tested, the requirements for a corresponding test system were derived. Ford implements a HIL test strategy with a Virtual Vehicle based on dSPACE hardware-in-the-loop simulators. In the individual phases of the ECU and network test cycle special tasks require special equipment. For each test phase the major solutions in hardware and software where described.

The custom library based approach to automated tests was presented. This approach provides a reduction in test execution time, increased reliability of tests due to the repeatability of external and internal conditions, and the ability to perform more exhaustive tests by easily modifying the test conditions. Furthermore, with this approach a high reusability of tests and test parts can be achieved.

REFERENCES

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