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ABSTRACT

Ford Motor Company has recently implemented a Hardware-In-the-Loop (HIL) testing system for a new, highly complex, hybrid electric vehicle (HEV) Electronic Control Unit (ECU). The implementation of this HIL system has been quick and effective, since it is based on proven Commercial-Off-The-Shelf (COTS) automation tools for real-time that allow for a very flexible and intuitive design process. An overview of the HIL system implementation process and the derived development benefits will be shown in this paper. The initial concept for the use of this HIL system was a complete closed-loop vehicle simulation environment for Vehicle System Controller testing, but the paper will show that this concept has evolved to allow for the use of the HIL system for many facets of the design process. Finally, the paper will demonstrate the benefits that have been achieved by using multiple HIL validation systems, to coordinate development with suppliers using the model-driven process, and to simulate conditions for testing that are difficult to achieve in actual vehicles.

INTRODUCTION

Recently, the automotive industry has seen a great change in the implementation process of new control systems, with the integration of rapid development tools for new ideas and products. Perhaps the bigger change, however, is the adoption of these same rapid-prototyping concepts for vehicle and component testing and validation, called Hardware-In-the-Loop (HIL) simulation. HIL simulation involves modeling the plant hardware (engine, transmission, vehicle dynamics, etc.) being controlled, and interfacing this model with the intended controller. In the past three years, Ford Motor Company has implemented such a HIL testing system for a new, highly complex, hybrid electric vehicle (HEV) system Electronic Control Unit (ECU). The implementation of these HIL systems has been quick and effective, since it is based on proven Commercial-Off-The-Shelf (COTS) automation tools for real-time that allow for a very flexible and intuitive design process. This has provided even greater benefits, since the simulation interface between controller(s) and plant is followed during all phases of the development and testing process. It is well known that the costs of correcting errors are much less if they are found earlier in the design process.

The ECU strategy prove-out is done in successive steps on the desktop, HIL, dynamometer, and vehicle, with each step bringing in additional "real" substitutes for the virtual models. Testing in this sequence has two important advantages. First, it ensures that component level testing is done prior to subsystem and system level testing. Second, it capitalizes on the fact that ECUs are

usually available much sooner than vehicle hardware prototypes, enabling a large amount of testing to be completed prior to a vehicle build. Figure 1 graphically describes the steps in ECU validation. [1]

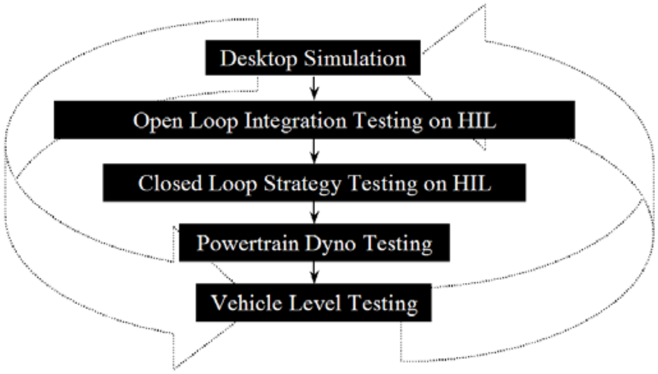

Figure 1: ECU Validation Process

Many benefits have been achieved with HIL testing. Suppliers have started using HIL systems to actively validate their individual subsystems. The HIL systems have been duplicated in multiple locations, which run the same models so that testing can be done on "identical" vehicles. Another benefit is that these HIL system models have improved the communication of specifications between suppliers and OEMs. These HIL simulations give the test engineer the ability to simulate a variety of scenarios that may be too difficult, time consuming or expensive to do on a vehicle prototype. This advanced testing capability has proven to significantly reduce the overall development time and greatly improve the quality and reliability of the final product.

HISTORY OF THE HIL IMPLEMENTATION

HEV DEVELOPMENT CHALLENGES

The development of an integrated Vehicle System Controller (VSC) for a HEV vehicle posed several validation challenges for Ford. The VSC was a fresh design, and thus existing validation procedures, knowledge bases, and infrastructure did not exist. More importantly, validating this system solely on a vehicle, as is typically done, would have been prohibitive for several reasons:

1. Validation of the VSC function needed to proceed in parallel, or prior to other HEV system controller or hardware availability.

2. Development vehicle availability would be extremely limited due to cost and other development needs.

3. Validating some control interactions on vehicle would likely have been extremely difficult or damaging to system hardware.

These challenges presented an ideal opportunity to apply HIL testing technology. Visteon was approached for assistance in implementing such a system due to extensive experience in applying HIL technology to powertrain control validation [2]

It was desirable to fulfill Ford HIL requirements for the HEV test environment with as much COTS technology as possible. This would minimize development costs and reduce lead times to implement such a system. Leveraging existing system configurations used at Visteon, a decision was made to utilize a dSPACE midsize HIL simulator system with slight modifications (Figure 2). An extension for extra I/O channels and a current measurement board was added to the base system.

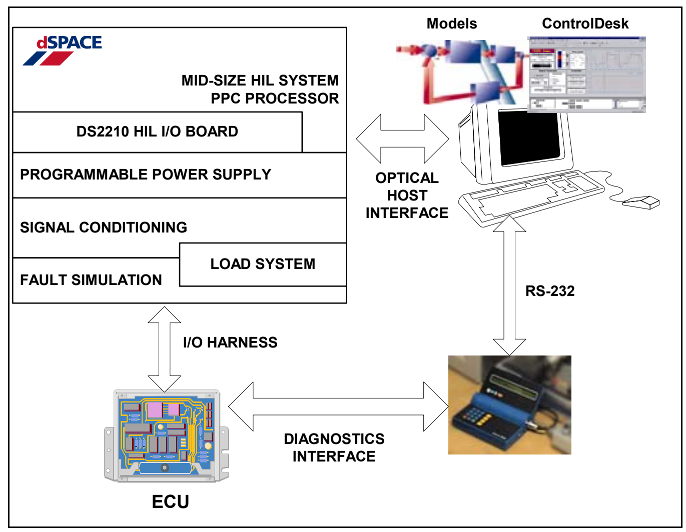

Figure 2: HIL system architecture diagram

VALIDATION CHALLENGES

The requirements for validating a VSC for a HEV control system also presented new challenges:

1. Sufficient computational power was needed to execute not just an engine plant model, but models of other controller units as well as a complete vehicle model. This was needed for the eventual use of closed loop drive cycle based testing.

2. The system must also accommodate automatic fault management as part of a closed loop testing methodology [3]. These faults needed to be under simulation control such that faults could be induced during automatic drive cycles. Initially, this was a key attribute of the HIL system since it addressed the need to test conditions too extreme or difficult to test in the vehicle.

3. The system must be capable of extensive CAN communication support since the HEV controllers communicating with the ECU were to be modeled.

4. The same system must be capable of open loop operation as well as closed loop operation with essentially the same user interface environment. The dSPACE HIL system provided this capability with ControlDesk as well as an environment to easily modularize use of open loop and closed loop models.

HIL SYSTEM OVERVIEW

HIL SYSTEM BASED TESTING

In the past 20 years, there have been many projects that have validated the success that can be achieved using HIL system testing [3,7,1]. dSPACE HIL systems have been involved in many of those programs. Originally, due to the lack of availability of standard hardware, many of these systems were built from custom or specific components. There was also the general need for actual hardware in many of these systems, since the modeling capabilities of the developers or the processing power of the systems lacked the capability to accurately reproduce plant behavior. The engineers at dSPACE gained significant capabilities in the assessment of the functions needed in these areas and developed the hardware needed for more accurate simulation capability. In the late 90's, dSPACE launched a scalable COTS line of HIL systems, which would allow for application to a diverse variety of customer requirements.

HIL Hardware Systems

The dSPACE HIL systems use a modular board subsystem approach to supply the processing throughput and necessary I/O for the customer applications to properly function in real-time. This system allows for model scalability by easily adapting parallel processing power if needed. The system also has many configurable I/O boards, which provide the necessary I/O functions, and even allow for parallel I/O subsystems, to guarantee faster throughput, if needed.

In addition to standard processing and I/O functions, the proper signal conditioning for sensor and actuator interfaces is needed. This allows standard boards to interface to automotive voltage levels and provides component modeling capability. The heart of the system (Figure 3) used for this project is the DS2210 HIL I/O Board, which provides the following capabilities:

1. On-board signal conditioning for automotive voltage levels

2. Support for up to 8 cylinder engine simulation, which is fully synchronized through an angular processing unit (APU) time base

3. Automation of the data capturing process for Injection and Ignition signals

4. Many additional I/O channels for various switch, sensor, and actuator simulation

5. User-definable multiple Crank and Cam waveforms for engine simulation, which can be selected by the user or model on-the-fly

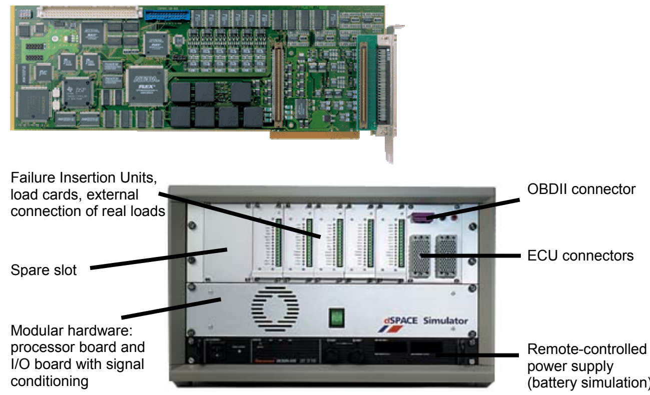

Figure 3: DS2210 HIL I/O Board and HIL Hardware

Other components of the dSPACE HIL Systems that allow for functional testing are the Load Rack and Failure Insertion subsystems. Proper loads need to be supplied for ECU outputs, in order to prevent diagnostics errors from occurring during testing. The interface from these loads is then subsequently interfaced to the HIL system inputs. The dSPACE HIL systems allow for easy insertion of simulated loads in the HIL chassis. These load boards also provide an interface for connection of actual loads (such as throttle body, etc.), if they are needed for testing. The Failure Insertion Unit (FIU) system is a configurable network of relays, which allow any of the ECU outputs (and sometimes inputs) to be shorted to battery or ground and also open circuited. These software-controllable FIUs allow for any ECU diagnostics to be tested by simulating expected failures. They also allow for testing of such failures in extreme or unanticipated conditions, which can be virtually impossible to duplicate in actual test vehicles.

USER INTERFACES AND TEST AUTOMATION

The software that is used in the dSPACE HIL systems is ControlDesk. ControlDesk handles every facet of the HIL usage process, from providing customizable user interfaces, to managing the model execution and all hardware configurations, to providing extensions to the HIL environment such as test automation. Realistic Graphical User Interfaces (GUIs) can make the system more user-friendly for engineers (Figure 4). All model parameters and data can be either modified or acquired by ControlDesk, giving ultimate control over the simulation process.

The HIL usage process may involve interfacing to external hardware, simulating failures, or even just setting up the proper test environment with model initial conditions. ControlDesk uses the test scripting language Python to give the test developer full control over the test environment. Using Python test automation, the engineers at Ford have been able to make HIL system usage as seamless as possible.

Figure 4: ControlDesk Layout for HIL User Interface

HIL test automation gives these systems huge advantages over manual environments for testing. These advantages allow for automation of tests, provide easier test reproducibility, and also facilitate the test development process with design tools. The latest generation of dSPACE test automation tools (AutomationDesk) provides advanced graphical test sequence design and full test process management [8]

MODELING STRATEGY AND PROCESS

Since the performance of the Electronic Control Unit (ECU) is tested in a virtual vehicle environment, the appropriate vehicle dynamics need to be modeled. There are four important elements to the HIL System model that is used for ECU testing [4]:

1. Models of the primary physical system being controlled (such as engine, transmission, battery, motor, etc.)

2. Models of the sensors that drive the input signals to the ECU (such as sensors for engine speed, transmission speed, engine intake manifold pressure, battery voltage, etc.)

3. Models of the actuators that are driven by the ECU (such as electronic throttle body, fuel injector, hydraulic valves in the transmission, etc.)

4. Models of the external systems that interact with the vehicle system (such as human driver, ambient model generating ambient temperature, pressure, road grade, etc.)

The scope of the HIL system model is primarily driven by the level of functional testing required. At one end of the spectrum, the HIL test bed could be used as an open-loop tester to verify some low level (input/output driver level) ECU software functionality. In this case, the vehicle 'model' could be constant values or uncorrelated signal traces that drive all the inputs of the controller. At the other end of the spectrum, the HIL test bed could be used for verifying closed loop dynamic functionality. In this case, a simulation model of appropriate level of detail is required as the virtual vehicle. As a general rule, any vehicle behavior that influences the monitored performance of the ECU needs to be modeled. As examples, if the engine controller ECU is being tested, a detailed battery thermal model may not be required. Such a model may be required if the battery controller ECU is being tested. Similarly, while testing the battery controller ECU in a HIL setup, a detailed model of the engine intake manifold dynamics that captures the dynamic response of the engine to changes in flow of EGR and fresh air may not be required.

Two kinds of simulation model configurations were used to test each ECU version. The first kind (Figure 5), called the Open-Loop Test Platform (OLTP) [1], models only the low level system I/O functionality and any critical feedback paths in the system (such as input to controller Signal X has to go from Low to High state within 200 milliseconds after an output of the controller Signal Y is switched High by the controller). The simulation of the physical plant is not included in the OLTP.

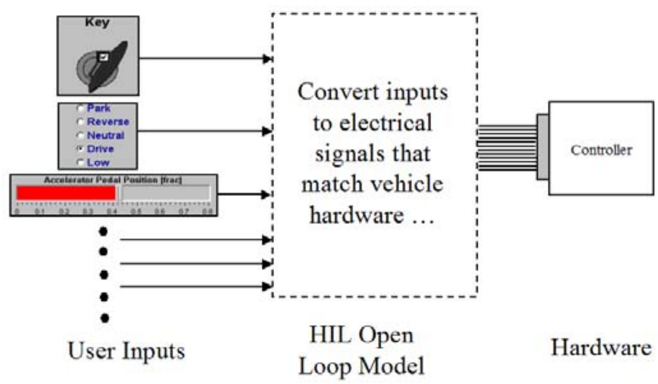

Figure 5: Open Loop Test Platform

The second kind (Figure 6), called the Closed-Loop Test Platform (CLTP) [1], models all the physical plant behavior in addition to the I/O processing. Both test platforms found extensive usage in the controller development process. In the initial stages, when the system hardware was not completely 'frozen' and the control algorithms were preliminary, the OLTP was very useful to test all the low-level functionality of the controller module. As the project matured, the controller module could not be executed successfully (without triggering any faults) without the CLTP. This was due to some of the advanced diagnostics features in the controller software, which required appropriate closed-loop behavior. If such closed-loop behaviors are not simulated, the controller software goes into fault modes and changes the controller responses significantly. In the

early stages of this project, it was felt that OLTP would not very useful for such an advanced new technology vehicle. But, the usefulness of the OLTP far exceeded our initial expectations.

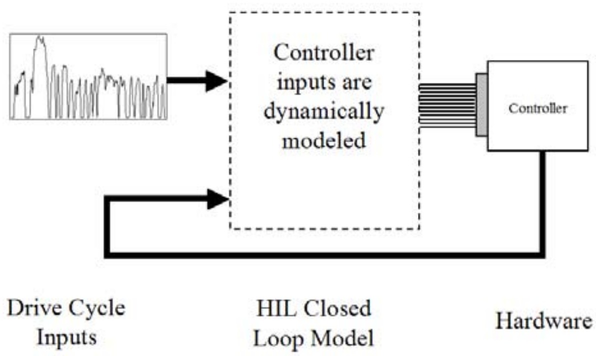

Figure 6: Closed Loop Test Platform

A model based control system development process was used in this hybrid electric vehicle project [10]. Hence, vehicle simulation models were used extensively in desktop simulations during the development of the control algorithms. The vehicle simulation models consist of all the key hybrid electric powertrain components such as internal combustion engine, transaxle, high-voltage battery and transmission gear train.

The model architecture was flexible in the sense that the component models were re-configurable. A concept similar to the 'Configurable Subsystem' block in Simulink®[1] was used to ensure flexibility in the model architecture (see [5,6] for a similar concept discussion). This modeling flexibility was leveraged to use appropriate levels of details of model components in the system development for (1) simulation based analysis for fuel economy and performance prediction and (2) control algorithm development and desktop validation. The desktop simulation models were used for the HIL test bed after suitable modifications. The model itself is a vehicle level model and has been architected as follows. Referring to figure 7, there are three primary subsystems; the driver model, the controllers subsystem and the plant subsystem [10].

[1] Simulink is a registered trademark of The Mathworks, Inc.

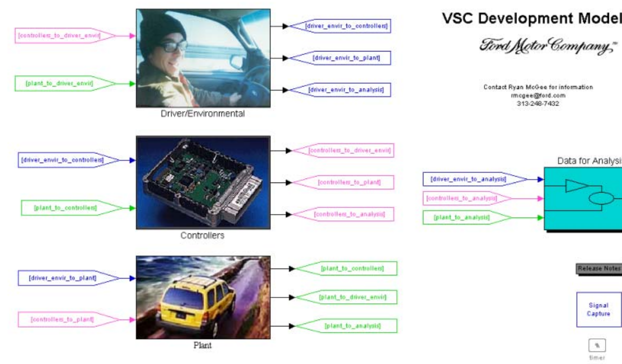

Figure 7: Ford HIL Model Subsystems

Due to the flexible modeling environment, the same architecture was reused for HIL simulation with real-time compatible model choices for the component models. To move from desktop to HIL environment, the choices for the controller model components were switched to the 'HIL option'. Within 'HIL option', the user further selects the version of the controller that he/she wants to use. In the 'HIL option' controller block, the VSC and the engine controller models were replaced by stubs that communicated to the physical powertrain ECU (that included the VSC and the engine controller) via the HIL. Several elements of the plant (as described in an earlier section in this paper) were remodeled with higher fidelity, to allow the smooth operation of the ECU and to prevent it from getting into any failure modes. This configures the HIL system model for compilation and execution (see Figure 8). Such a flexible environment allowed rapid migration of desktop (non real-time) simulation model changes to the HIL (real-time) environment.

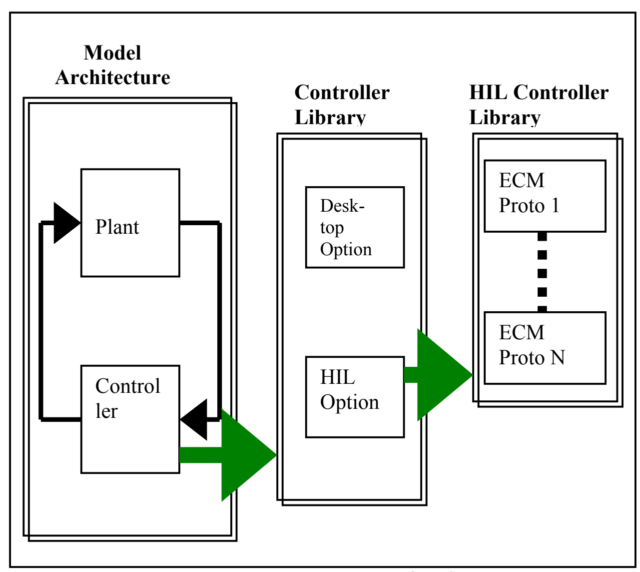

Figure 8: Flexible Model Configuration

One of the keys to success has been the inclusion of controller and subsystem models that were provided by (and are continued to be maintained by) certain key suppliers. Additionally, since Visteon was the supplier of the ECU, they already had access to the I/O circuits of the ECU and this eased the implementation of the ECU load circuits in the HIL.

After the desired model configuration is built for the dSPACE target hardware, and tested successfully, the experiments are saved and are run directly using ControlDesk without repeating the model build process. Multiple prototype control module versions (with both hardware and software changes) were successfully tested using such a flexible modeling environment.

Although the existence of desktop simulation models helped to reduce the HIL model development time, additional effort was needed to "tailor" the model to the HIL environment. Simplified actuator and limited sensor models were used in the desktop simulation environment since the core control algorithms without the I/O processing were being developed in the desktop environment. This desktop model was modified to include (1) relevant sensor and actuator dynamics and (2) enhanced plant dynamics that captured the functional behaviors influenced by the controller. Additionally, I/O processing models were developed to translate low-level hardware related signals to physical system variables.

The desktop model is simulated in non real-time while the HIL system model is simulated in real-time. Hence, the modeler has to ensure that the model computation time allows for real-time processing. The HIL system model was simulated with a fixed step size of 1 millisecond. This was found to be a good compromise between speed and accuracy. Some block level structural optimization had to be performed to ensure that the computation time was well within 1 millisecond. As the controller software matured, the size of the HIL system model grew. The growth in size was managed carefully to ensure that the real-time constraint was met.

The hybrid vehicle has several critical subsystems with individual control modules such as the engine, battery, transaxle and brakes. The controllers communicate with each other and with the Vehicle System Controller on a CAN based communication network. The behaviors of these subsystems are strongly influenced by their individual controllers. Not all of these control modules were connected in the HIL setup. Those controllers that were not connected as hardware pieces were simulated as models along with the plant dynamics on the HIL system. So, the communication between controllers and the controller functionalities had to be modeled carefully to ensure a good compromise between functional accuracy and real-time constraints.

Component data was obtained to calibrate the models. Both steady state and transient data were collected on the subsystems. The individual component calibration process was repeated to get the updated parameter sets whenever any of components were changed.

Model validation is an important step in the set up of the HIL system. The notion of validation is so broad that there is no single metric that works in all scenarios. In our case, the model validation was done as part of HIL system validation, which is described in a later section of this paper.

SYSTEM USAGE AND BENEFITS

HIL SYSTEM PROCESS AND USAGE

As stated earlier in this paper, the primary purpose behind the usage of the HIL was to allow verification of the Vehicle System Controller (VSC), which is part of the primary powertrain ECU. Since the VSC was a Ford first, there was little test infrastructure that already existed to enable its testing. This had its pros and cons. The cons included the fact that significant effort had to be expended to develop an environment that could suitably test the VSC. The pro was that we were able to utilize modern technologies, without being hampered by legacy equipment. It was felt that it was imperative to have a means to sufficiently test out the VSC operation in closed loop, and that a HIL system with a vehicle level model was the solution.

That being decided, the team that would put such a test environment together was structured to draw upon the skills and experience from a variety of groups. Ford provided the system specifications, and Visteon led the system design and integration.

Visteon's experience with HIL systems and the fact that they were the supplier for the control system made them a natural choice. dSPACE supplied the HIL hardware and software. Emmeskay was also selected as part of the team because of their strong modeling experience.

The initial concept for the HIL system was for complete system model testing and ECU verification, but this “system-level” intent has evolved. Open loop test capability was developed first and was utilized as the first stage of software verification. As the strategy became more mature, and as higher level functional testing was required, closed loop test capability was developed. The ECU strategy prove-out is done in successive steps on the desktop, HIL, dynamometer, and vehicle, with each step bringing in additional physical substitutes for the virtual models. Testing in this sequence has two important advantages: First, it ensures that component level testing is done prior to subsystem and system level testing. Second, it capitalizes on the fact that ECUs are usually available much sooner than prototypes, enabling a large amount of testing to be completed prior to a vehicle build.

Our verification test process follows the System Engineering V (Figure 9), with software feature (or unit) level testing done prior to functional (or system) testing. We have found the HIL to be an effective tool to perform thorough software feature level testing. The open loop testing capability is what tends to be most utilized in this phase. HIL testing has been incorporated into the prove-out process of the ECU, so now it is done as a matter of course. Closed loop testing is primarily used when an entire drive cycle is simulated, because the controllers require feedback from the plant.

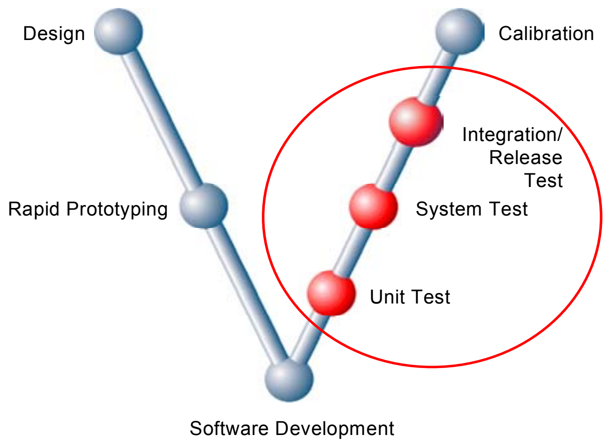

Figure 9: System Development V-Cycle

In addition to the above, the HIL is part of the process of the software application testing. The application in this context refers to an entire software release for the ECU. The application is tested under various scenarios encountered in normal real world driving. It is also run through prescribed drive cycles. The results are processed and provided to several teams. The advantages of this are discussed in the Benefits section below.

Because the ECU gets more complicated with time, we budget a certain amount of time over the course of the year, to maintain and upgrade the HIL hardware and software. Not doing so could result in failure modes of the ECU being tripped (which is undesirable unless being specifically tested for).

HIL SYSTEM PERFORMANCE VS. ACTUAL VEHICLE TEST DATA

Once it is decided what types of tests would be run on the HIL, the models were validated to ensure that the simulation produced good results in the areas of interest. As new vehicle prototypes were built and new control strategies were released, the desktop model (that the HIL model is based on) was regularly validated against new vehicle data. This gave the HIL model a jump-start in its validation. Driver data (such as accelerator and brake pedal positions) from specific drive cycles was input into the HIL model, and the outputs of the HIL model were compared to the vehicle data from those same drive cycles. The model was then updated to provide a fairly good match between vehicle and model data.

The validation work has been discussed in more detail in [10]. Overall, a reasonable correlation of the vehicle test data and HIL system simulation data was found. The correlation was sufficient to provide a good level of confidence in the usage of the HIL system for software validation. As an example, the traction battery power usage for vehicle level data and HIL simulation data is shown in Figure 10. The same driver commands recorded during the vehicle level test were used to actuate the HIL model. This is a close up view of one driving maneuver, but similar results were found for a variety of driving conditions.

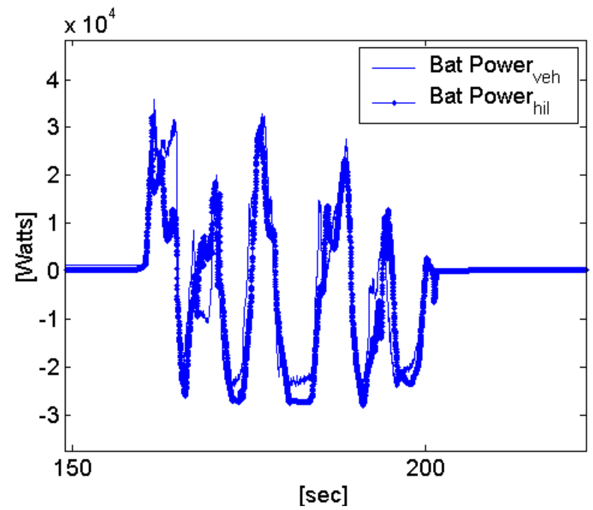

Figure 10: Validation Data

BENEFITS OF USING THE HIL SYSTEM

Many benefits have been achieved with HIL testing. The HIL systems have become efficient tools for strategy and interface software development. On the Ford project, HIL testing began early in the development of the ECU. In total, it has been used for four prototype phases of the ECU. Metrics are being collected on why a typical engineer uses the HIL, as opposed to some other testing platforms (such as desktop simulation or the vehicle) that may or may not also be available. What can be unequivocally said is that the usage of the HILs has far exceeded our original expectations. We first conceived of using the HIL for testing the VSC, but now it is being used to test a large portion of the ECU. The hybrid project began with one HIL system (for VSC/ECU use) and that has since expanded to three. To keep maintenance costs low, as well as personnel, we decided that these three HILs would, by and large, be identical to each other.

These HIL simulations have given the test engineer the ability to simulate a variety of scenarios that may be too difficult, time consuming or expensive to do on a vehicle prototype. This advanced testing capability has proven to significantly improve the quality of the released software.

We find that on our project, the HILs are heavily utilized around the period that a new software release is due. Usage further spikes when this release is on a new prototype of an ECU of which there are limited numbers available. This is to be expected, because now there are fewer available test environments (in terms of vehicles, electrical breadboards and the like) for the engineers to do their testing.

The benefits of testing the software application after each release are three fold. First, it ensures that the application is performing per design. Second, the data collected during the drive cycle testing is processed to calculate certain vehicle attributes of interest, for example, performance and fuel economy. This is used to provide early feedback to vehicle attribute leaders on how a new ECU software release affects their attributes. Third, the HIL provides an environment to do a *reproducible* vehicle level test of an application. Since the HIL configuration can be accurately recorded, and the HIL models are version controlled, it is relatively easy to reproduce the same testing environment at any point in the future, if needed. The reproducibility of testing afforded by the HIL environment is far greater than that of a vehicle prototype, which is typically scrapped in a year or so. The results of the application testing are also version controlled, and if ever called into question in the future, the HIL environment can be relatively easily reproduced to rerun the test.

One area of functional testing where the HIL shines is in CAN network failure mode testing. Faults can be simulated with an ease that is not possible on the vehicle. Several other faults, such as electronic throttle control faults, or major subsystem failures resulting in Limited Operating Strategies, are simulated and their results examined on the HIL. The HIL allows the engineers to reproduce scenarios that may be difficult and expensive and of the type that would only be done on a test track under controlled conditions. It also avoids the development of customized ECU software to be able to create such conditions on a vehicle [9].

The HIL system has also been used to study the chronometric usage of the ECU. We have done back-to-back HIL and vehicle testing under similar driving scenarios and have verified that the chronometric usage of the ECU under both conditions is similar. As a result, chronometrics are regularly monitored on the HIL prior to a software release and the flag is raised if CPU idle time falls too low.

Another area where the HIL system is used is in the development of reasonable initial calibration values for the embedded software. Still another is in the debugging of issues. The open loop and the closed loop environments offer more flexibility in being able to analyze issues than is available on a vehicle or a powertrain dyno.

The HIL system has allowed a lot of control function development to be done and verified ahead of a vehicle build. Part prototypes are often available prior to a vehicle prototype, and can sometimes be hooked up to the HIL system for function execution and verification. The improved software quality and early verification of software translates to (1) Reduced vehicle commissioning time and (2) reduced vehicle test time. (Note that vehicle commissioning refers to the process whereby an early vehicle prototype is put together and each function is verified at a gross level, to see if a minimum level of functionality exists (e.g. the vehicle can be started and driven) before being handed off to the various engineering teams for further development.)

As the ECU software matures and gets more stable, another benefit that we have explored is that of automating the tests that are run on the HIL. The design verification methods can be automated through the use of scripting tools. We are looking into automating test execution, data acquisition and analysis and report out. The benefit here is that of reduced test times, as well as fewer test personnel.

The success of the VSC validation effort through HIL usage has prompted other subsystems within the hybrid project to do the same. Suppliers have started using HIL systems to actively validate their individual subsystems. The HIL systems have been duplicated in multiple locations, which run the same models so that testing can be done on “identical virtual” vehicles, at a fraction of the cost. Another benefit is that these HIL system models have improved the communication of specifications between suppliers and OEMs. Some work has also been done to create a HIL system that contains more than one “real” controller. This allows yet another layer of testing to be done, at a little higher up on the V-cycle between the desktop simulation and the vehicle levels.

CONCLUSION

This team of authors has had a 3-year experience with the HIL system in the development of the ECU for a hybrid electric vehicle. In that period of time, the HIL has gone from a system that was intended to test only the vehicle system controller portion of the ECU to one that is part of the verification process of the entire ECU. Usage has also expanded from one system into three. A large number of control engineers have developed an appreciation for this technology and its value in the ECU verification process. We recommend that such a technology be made part of the standard process of ECU development.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

CAN	Controller Area Network
CLTP	Closed Loop Test Platform
COTS	Commercial off the Shelf
ECU	Engine Control Unit
FIU	Fault Insertion Unit
GUI	Graphical User Interface
HIL	Hardware-In-the-Loop
HEV	Hybrid Electric Vehicle
HW	Hardware
I/O	Input/Output
OBD	On Board Diagnostics
OEM	Original Equipment Manufacturer
OLTP	Open Loop Test Platform
PCM	Powertrain Control Module
RTOS	Real Time Operating System
VSC	Vehicle System Controller