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Testing Electrified Drivetrains for Vehicles without the Battery Pack or Engine.

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Abstract

The hybrid electric vehicle (HEV) is becoming a sustainable vehicle architecture with the US government pouring 14.4 billion[1] into stimulus projects that support drivetrains of new vehicles that are series hybrid, parallel hybrid, or completely battery powered (BEV). Both the series hybrid and BEV have 100% of propulsion energy coming from electricity. The series hybrid uses an internal combustion engine (ICE) to power a generator that produces electricity. The parallel hybrid powers the vehicle by a mechanical combination of electric motors and ICE. In all cases, the drivetrain needs an electric motor, a traction battery and an auxiliary method of obtaining electricity. These auxiliary power units (APU) are typically a downsized, highly efficient ICE or fuel cell for a zero emissions alternative. Horiba's Virtual Engine (VE) and Virtual Battery (VB) are HIL[2] products that allow electric motor based drivetrain development without waiting for the new battery pack and ICE to become available. Relevant product features for HEV development are discussed in terms of form, function, and verification with data.

[2] HIL commonly referred to as hardware in the loop where something physical is used to create power, or run programs, or create a response but inputs and outputs are simulated from a mathematical model of their real end use condition.

Keywords: Virtual Battery, Virtual Engine, HIL, simulation, powertrain development

1 Introduction

Historically, the verification, validation & controller calibration of vehicles was brought in from the proving grounds to the laboratory using a chassis dynamometer(CD) simulating the road. Figure 1 illustrates this concept using Horiba's automation system (STARS) providing test schedules and data acquisition, dynamometer controller (SPARC) providing real time controls and simulation, and VULCAN 2WD chassis dynamometer providing the load to the vehicle.

Figure 1

The difficulty here is that the entire vehicle needs to have all its intended components in a pre-production state. By expanding the simulation capabilities of the dynamometer controller to include simulation of missing subsystems not under development, subsystem or component testing can occur anywhere a dynamometer can be

[3] ECU, Engine Control Unit; BMS / EMS , Battery Management System + Energy Management System; PCU/TPIM, Power Control Unit aka Traction Power Inverter Module aka Integrated Power Electronics....; TCU, Transmission Control Unit; ABS, Anti-lock Braking System,; ESC, Electronic Stability Control

conveniently connected, Figure 2 illustrates this concept for the physical ISG[4] electric motor being developed for a HEV. The vehicle's kinematic characteristics, tires, differential, transmission, and torque converter are simulated for their power flow to result in torque or speed set points to the dynamometer attached to the ICE crankshaft output.

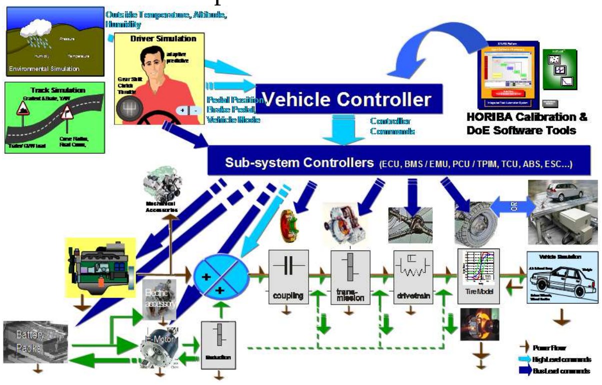


Figure 2

[4] Integrated Starter and Generator (ISG) is an electric motor attached to the crankshaft of the ICE that acts as motor to start the engine and as a generator of electricity when the ICE is running. Since it is directly on the crankshaft, this becomes a parallel hybrid vehicle. Electric motors used vehicle propulsion are called E-MOTORS to distinguish their unique construction and power output.

This configuration suffers from the lack of availability of the ICE and battery pack intended for the vehicle. Both are high value, sophisticated subsystems undergoing their own development process involving different parts of the organization and supplier network. E-motors are also being considered at other locations in the drivetrain. They can be located in the wheels, differential, transmission, or front end accessory drive (FEAD) in addition to the end of the crankshaft. These various alternatives add to the complexity of integration and calibration for the vehicle, thus requiring very early testing in the development process.

1.1 Quintessential Simulations

The power of the battery pack can be simulated by controlling the voltage output of a high power, programmable DC to DC converter using a real time model of the battery chemistry. This forms a Virtual Battery (VB) giving the dynamic and static performance of a battery pack. Additionally, the torque output of the ICE can be simulated on an electric dynamometer by a real time model of the combustion process and mechanical configuration. This forms a virtual engine (VE) giving an accurate torque signature rich in harmonics. Figure 3 illustrates the use of a VB and VE with actual hardware to produce the electrical and mechanical power. This report will point out VB and VE implementation, relevant features exclusively for HEV development, and comparisons to measured data from real battery packs and ICE.

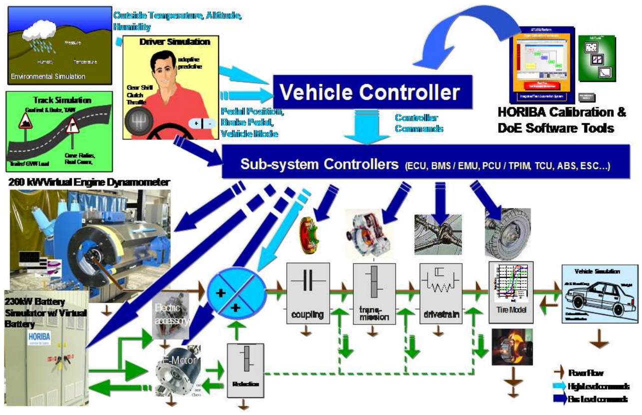


Figure 3
Simulation Diagram: VB & VE in drivetrain test stand (loading dynamometer not shown)

2 Virtual Engine Capabilities

The engine simulation controls the input dynamometer. Engine simulation provides sensor and data communication inputs to the transmission control unit (TCU) to mimic being connected to a the real engine. The engine simulation is influenced by ambient conditions (simulated or measured in the test cell) such as atmospheric pressure. Pedal position controls engine torque. Figure 4 is a block diagram of VE interface capabilities.

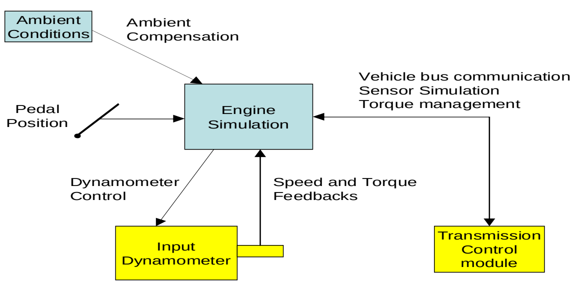


Figure 4 Virtual Engine Capabilities

2.1 Engine Simulation Functions for the Transmission Input

The engine simulation consists of operational maps, an engine controller, a parametric mechanical model similar to the mechanics engine, and an adaptive mechanism. The engine controller controls cranking (start & stop), idling and torque reduction during a gear shift. It also simulates the various engine/ECU delays. A parametric engine model calculates torque due to the kinematics of the parts (pistons, connecting rod, crankshaft, and flywheel) and gas pressures. An adaptive mechanism assures that the response torque amplitude follows the demand amplitude. It also provides a means to limit frequencies and orders.

Engine simulation provides the following functions:

1) inertia simulation,
2) throttle and pedal map simulation,
3) torque reduction during shift,
4) ECU torque management interventions,
5) engine cranking,
6) engine idle control,
7) ignition simulation,
8) coast simulation,
9) fuel cut and closed throttle simulation,
10) engine torque pulse simulation (ETPS) from the combustion process,
11) cylinder firing reduction,
12) front end accessory, generator loading, and
13) ambient condition adjustment.

ETPS includes simulation of fuel type (gasoline, diesel, CNG) and boost (turbo-charged, super charged or normally aspirated). Two and four cycle engines are supported from 1 to 16 cylinders. The following two figures show torque pulse waveforms at peak power of ICE engines being refined for HEV powertrains. These are characteristic torque signatures of the engine's mechanical configuration.

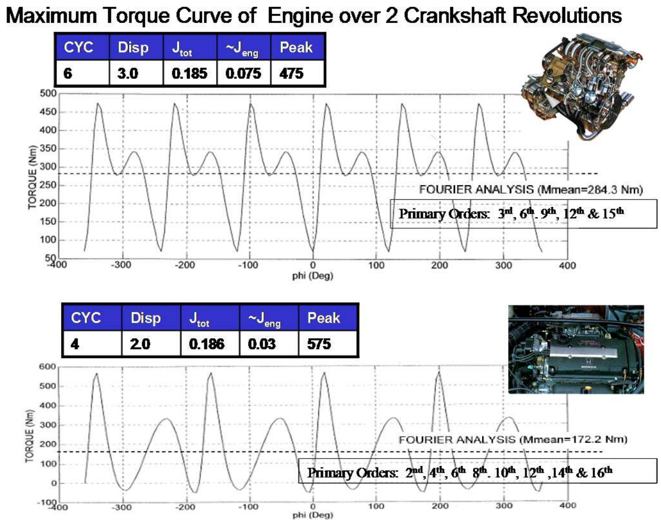


Figure 5

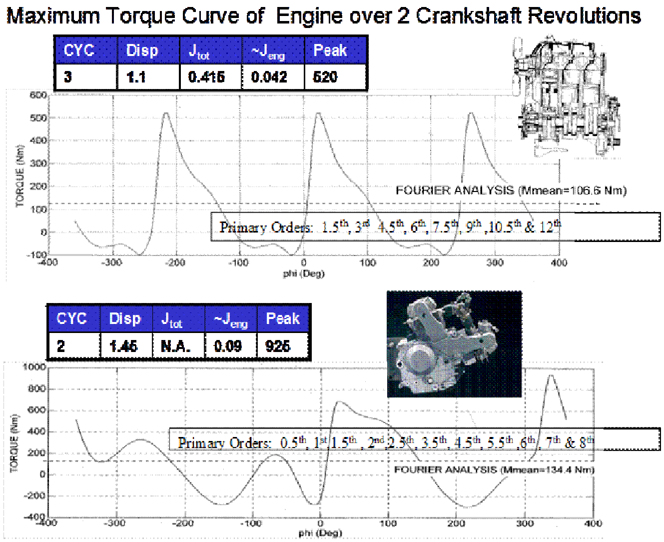


Figure 6

2.2 Pedal Map Simulation

Current generation engine technology uses fly-by-wire throttle control. This imposes additional simulation responsibility on the engine simulation to reproduce the demand from the "gas" pedal to throttle demand in the engine simulation. Typically this requires a set of maps found in the ECU to interpret pedal demand into throttle position. The throttle position is then sent to an engine map to create the proper engine torque output. Pedal mapping is highly dependent on vehicle calibration. Figure 7 shows an open loop approximation of pedal to throttle simulation.

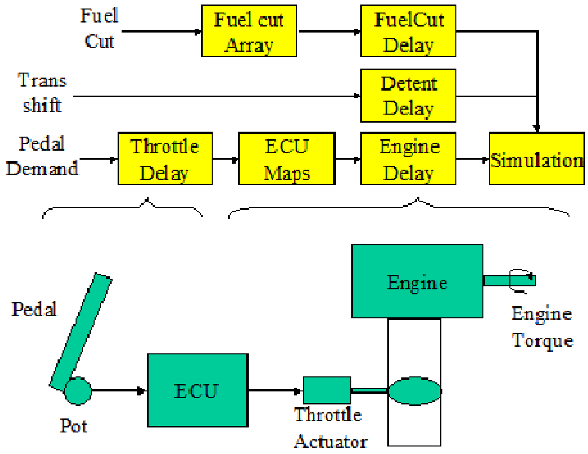


Figure 7

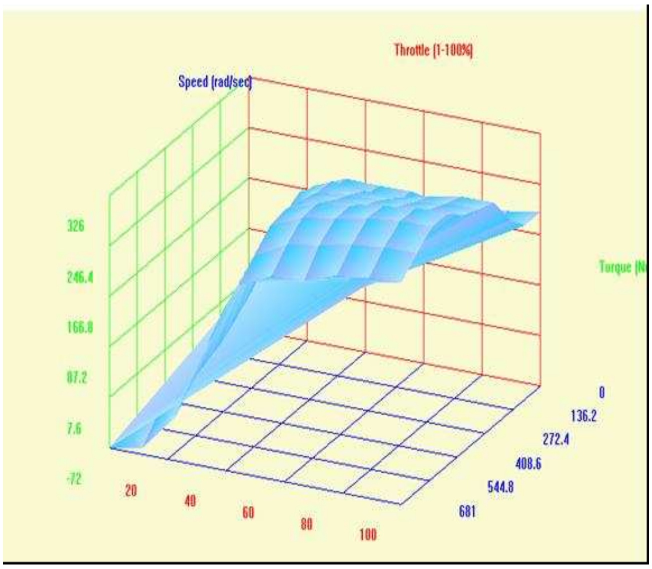


Figure 8 Engine Map

2.3 Engine Torque Map Simulation

An engine is typically throttle controlled. Based on the throttle setting and the current engine speed, the engine will produce a given torque. On the other hand, a dynamometer is speed or torque controlled. Unlike an engine, the electric dynamometer can produce maximum torque at zero speed. Some method is required in the engine simulation to limit the dynamometer torque to the average torque that the engine would produce and to create the throttle-to-torque function to mimic the engine. Engine torque Map Simulation (EMS) provides this capability. Engine features for performance and efficiency such as variable valve timing, Atkinson cycle, dual scroll turbo, and others are captured in the engine torque map when map is based on engine dynamometer testing.

Figure 8 is an engine map for the engine simulation. A throttle demand sent to the engine simulation is used along with the dynamometer's measured speed to determine the torque that the engine simulation should produce. Since many vehicles are now “fly-by-wire,” ECU implementations also provide additional mapping to map the pedal position to an internal throttle or torque demand. This additional pedal mapping may be a function of vehicle speed, battery state of charge, and other parameter(s) as the vehicle controller calibration deems appropriate. Obtaining the specific vehicle intent engine map makes the VE more realistic to the application.

2.4 Engine Inertia Simulation (EIS)

Drivetrain testing requires that the engine inertia is correct so that the load on the transmission or generator is equivalent between the real engine and the dynamometer performing the engine simulation. Often, the dynamometer inertia is larger than the engine inertia, so compensation (inertia simulation) is required. A combination of engine speed observers and feed forwards allow a robust implementation of the dynamometer torque (T_{el}) needed to simulate the inertia of the engine and its flywheel. This torque is added to the torque from the torque map simulation according to the following equation.

$$T_{el} = \frac{J_{el}+J_{FW}}{J_{sim}+J_{FW}} T_{eng} + \left(1 - \frac{J_{el}+J_{FW}}{J_{sim}+J_{FW}}\right) T_{trans} = K*T_{eng} + (1-K)T_{trans} \quad (1)$$

In figure 9, the VE is run in throttle/speed with the throttle ramped in an attempt to hold the torque relatively constant during a shift. During this part of the shift, the deceleration is constant. This results in the engine speed decelerating from 3900 rpm to 900 rpm. The speed change results in an inertia torque. If the dynamometer inertia and engine inertia are the same (top Chart), no compensation is required. The bottom chart shows where the dynamometer inertia is twice the engine inertia and the need to add compensation torque.

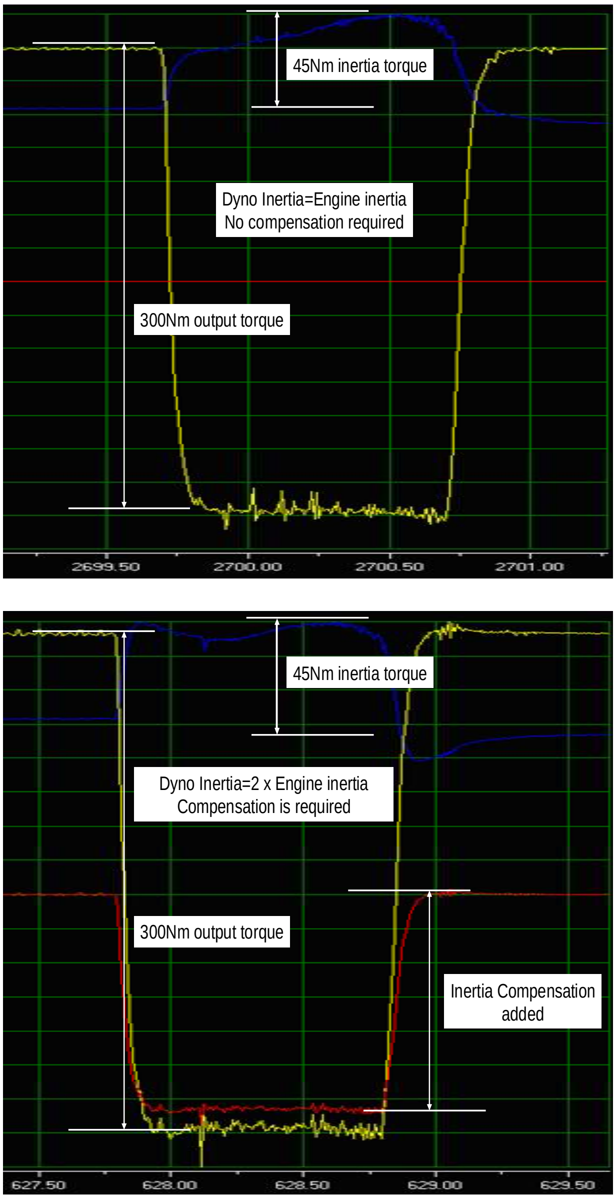


Figure 9
Simulated Torque without & with EIS

2.5 Engine Torque Pulse Simulation

Engine Torque Pulse Simulation (ETPS) creates the stroke by stoke torque requirements of the combustion process and superimposes the number of cylinders that result in the crankshaft output torque signature. Figure 10 shows an 8 cylinder engine running at 2000 rpm, part throttle with a mean torque of 118 nm. The mean torque is not shown on this display. Only the torque pulses are shown. We clearly see 8 distinct pulses, one combustion event in each cylinder, over the 720 degrees (two crankshaft rotations).

To produce 118 Nm of mean torque, we must produce 145 Nm of firing pulses.

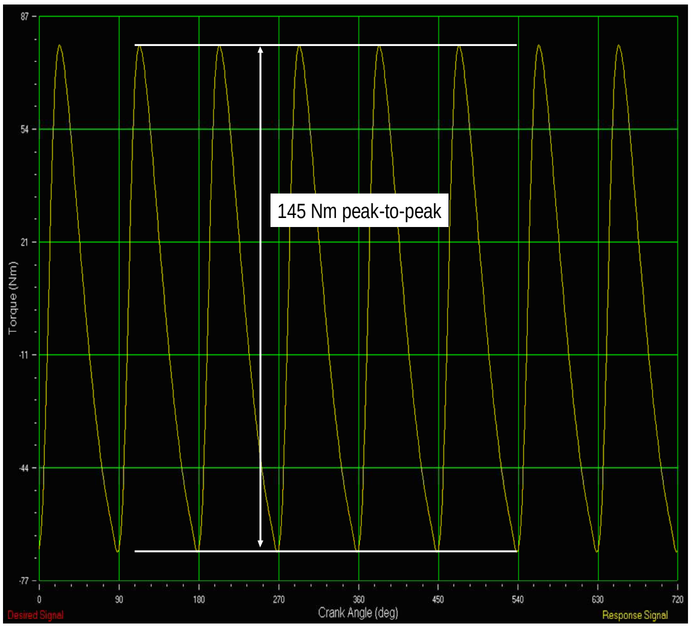


Figure 10
V8 torque over 2 crankshaft revolutions

2.6 Validation of Simulation to Real Engine Data

Validation of the engine simulation is crucial to the acceptance of the algorithm. A comparison between in instrumented crankshaft in a 4 cylinder gasoline engine (bottom chart) and the engine simulation (top chart) is shown in Figure 11. The correlation between simulation and the engine is excellent with the matching of firing order frequencies and closeness in amplitude.

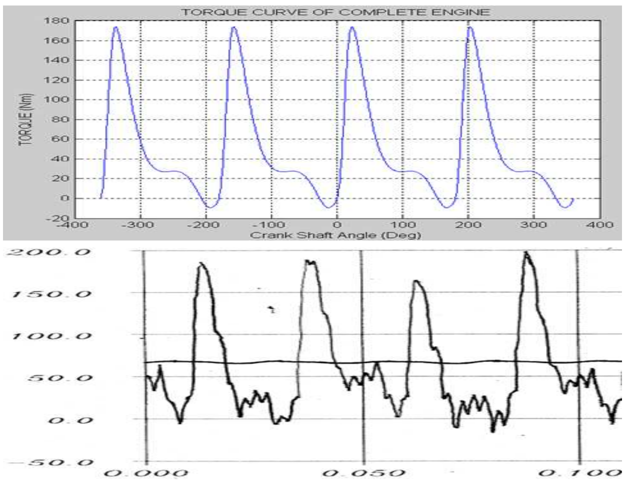


Figure 10

The lower graph is the output of a strain gauge on the rear most journal of the crankshaft. It shows the torque from the combustion process as well as torque from the resonances in the transmission. The upper graph is the output of the engine model.

Table 1 shows the amplitude of the spectral components of the engine simulation and the real engine. Inconsistent firing and certain torsional resonances from the transmission present in the measured data may attribute for the minor differences.

Table1: Engine Firing Orders Comparison

	Real Engine	Simulation
40 hz	37 nm	37 nm
80 hz	23 nm	30 nm
120 hz	8 nm	15 nm
160 hz	5 nm	7 nm
200 hz	3.7 nm	5 nm
240 hz	1.4 nm	2.5
280 hz	1.1 nm	2
320 hz	0.9 nm	1.5

2.7 Start up/Shut Down Simulation Including HEV Start

The typical startup profile for an engine is shown below. Idle speed, crank speed and their ramp rates are controlled. After cranking for a fixed period of time, the speed ramps up to idle speed and the idle speed controller takes over. Torque limits are placed on both cranking and idling. HEV startup for hybrids is easily parameterized by adjusting these parameters to shorter time intervals.

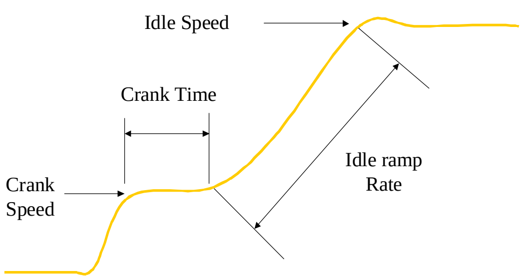


Figure 12
Tradition Start Profile

Engine shutdown/coast, as shown in figure 13, is controlled by the ignition, engine map near zero speed and the **StandStillSpeed** value. The engine map determines what torque is applied to cause the engine to stop. The StandStillSpeed value determines when the dynamometer command is zeroed.

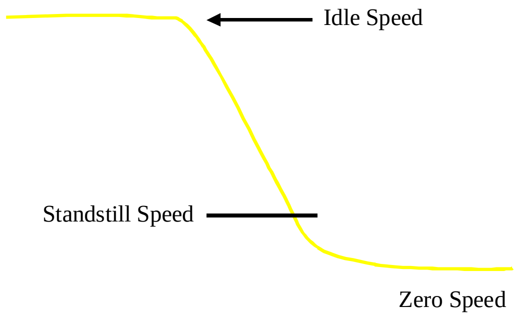


Figure 13
Engine Coast / Stop Profile

Figure 14 shows engine startup simulation with ETPS (engine torque pulse simulation) turned on. Note that for all engine simulation, torque pulses can be turned on or off. If turned off, then only mean engine torque is simulated. The engine first cranks for a short time after which the engine starts firing and accelerates to idle speed. Prior to firing and during cranking, engine torque pulses are the result of pumping forces in the engine.

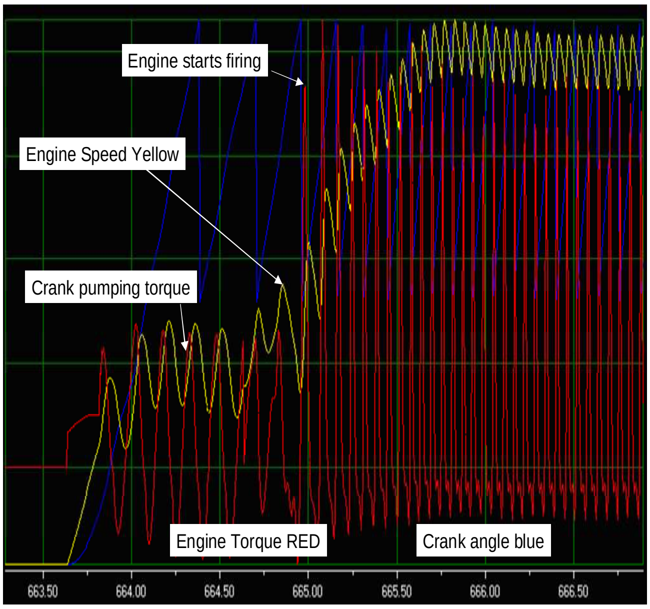


Figure 14: Example of Engine Start

2.8 Special requirements for Dynamometer used for Engine Simulation

The dynamometer needs a proper torque to inertia ratio to accomplish > 50,000RPM/sec accelerations and sub millisecond current rise times required for engine torque pulse simulation. Physical rotor properties (inertia and stiffness) must have a first order torsional natural frequency > 600Hz when connected to the transmission under test. Additionally, engines position in the real vehicle is duplicated by the tilt and height adjustment of the support base.

Figure 15 pictures a 0.084 kg-m2 inertia, 800Nm peak torque, engine simulation dynamometer designated as Dynas TP260. This dynamometer has been used to simulate 2 to 10 cylinder engines up to 350HP. This dynamometer can serve a dual purpose by testing e-motors up to 18,000RPM.

Figure 15: DYNAS 260M550TP(LC)

3 Battery Pack simulation for BEV & HEV Drivetrains

HEV and BEV (Battery (only) Electric Vehicle) drivetrains require a battery or a battery simulator to test the electric motor. Horiba provides a battery simulator to provide the power to operate the HEV motor. The battery simulator consists of a power source to supply DC power and the software to simulate battery conditions and control the supply of voltage and current from the power source. Interface cabinets connect the power source to the customer specific HEV electric motor controller (PCU, TPIM, other).

Demand for power, current, voltage, or power + additional current can be used to simulate battery operating modes. The battery simulator simulates realistic battery output current, output voltage, power, state of charge (SOC6), pack temperature, cell/module temperature difference, power limit, pack resistance, and capacity. Battery pack life (new, 5 years old, 10 years old) is simulated by adjustments to capacity and slew rates.
A battery pack is configured based on cell chemistry and the number of cells placed in series and parallel. Any nominal voltage, power, or capacity can be configured. Figure 16 is a high level block diagram of the VB system.

[6] SOC - State of Charge is a calculation of the BMS showing charge availability of the battery pack

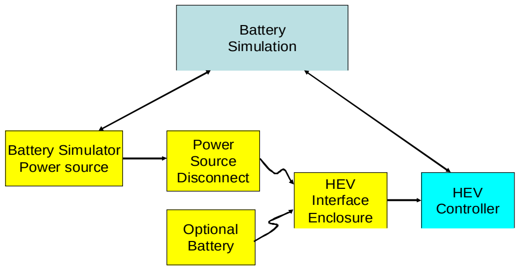


Figure 16: Virtual Battery (VB) Block Diagram

3.1 Different Battery Technologies Simulation

A number of HEV battery pack models incorporating chemistries such as Li-Ion, LiFePO4, NiMH, and Lead Acid AGM[7] are supported by the battery simulation software. In addition, interfaces to simulate RLC (resistor-inductor-capacitor) based custom, user defined, battery models are provided.

Horiba's real time model is based on a proposal from Min Chen in the IEEE Transactions on Energy Conversion, Vol. 21, NO2 June 2006 and is shown in figure 17.

[7] AGM - Absorbed glass mat and Gel Batteries are classifications for low maintenance valve regulated lead acid (VRLA) battery

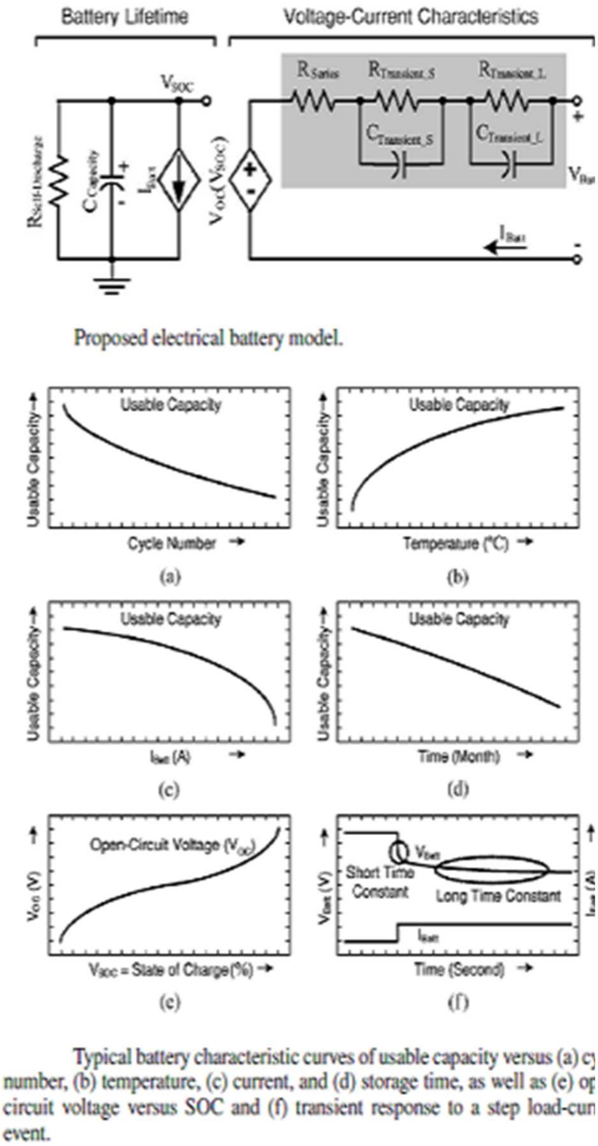
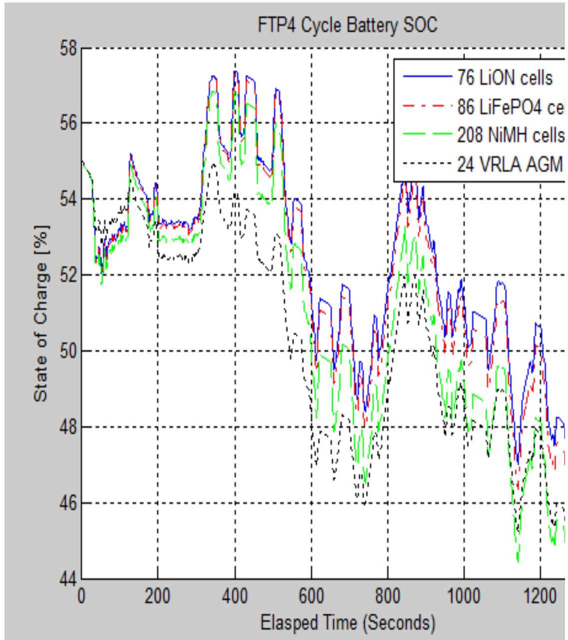


Figure 17 Battery Cell Equivalent Circuit

3.2 State Of Charge Simulation

The battery simulation incorporates SOC (state of charge), DOD (Depth of Discharge), and power limits to simulate the HEV/EV/PHEV battery packs. Shown in figure 18 is the state of charge of various battery pack chemistries over a 23 minute FTP (Federal Test Procedure) simulation.



3.3 Temperature Effects Simulation

The battery simulation incorporates thermal simulation to show temperatures values in the battery pack. Shown below is a simulation of temperature for the various battery technologies. Besides the heat produced by the battery pack, temperature affects every single parameter and condition of each battery cell. All of these parameters and variables must be updated as a function of temperature as well as energy use.

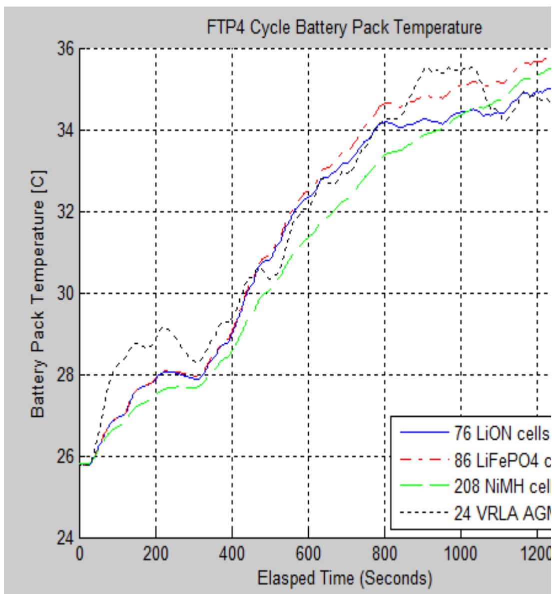


Figure 19: Battery Pack Temperature

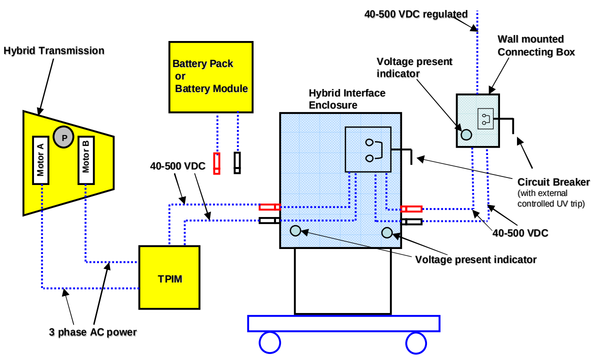
3.4 Residual CanBus Simulation

A complete simulation of the battery pack requires CAN (or other vehicle bus) communication with the TCU or ECU. For instance, the TCU may require state of charge to determine if the HEV motor can provide power or should the engine provide power. Likewise, the e-motor can fill in the torque "holes" during a shift when the vehicle is in a powersplit mode.

The Horiba real time controller, SPARC, provides six separate CAN channels to support this communication. Approximately 200 variables are available to be sent or received over each CAN bus channel and to or from the battery simulation. This allows grouping of messages to a specific consuming controller.

3.5 Interconnects that Support Battery Simulation

Of crucial importance is that power must be safely distributed in the transmission test cell. Convenient plug-in style connectors provide safe connection to the HEV motor controller and power source for voltages up to 600Vdc. Two interface cabinets provide connection between the transmission HEV motor and power. The first cabinet (hybrid interface enclosure) connects the HEV motor controller to the power source. The power source may be the battery simulator or it may connect to an actual battery. The second cabinet, the wall mounted connecting box is the DC power disconnect. It provides connection between the battery simulator power source and the hybrid interface cabinet. The two enclosure system assures safe, convenient connection between power source and HEV motor as well as connection to measurement devices



.Figure 20: HEV Interface Enclosures

Shown below is the hybrid interface enclosure. The front view shows the disconnect and power on indicators. This enclosure provides loss of isolation detection and it is connected into the emergency stop chain to support power removal without damaging the HEV motor controller. It is rated up to 600 VDC. The enclosure rear view shows the plug in power connectors.

Enclosure front view Enclosure rear view

Figure 21: In-Cell HEV Interface Enclosures

3.6 Comparison of Voltage, SOC, & Temperature to Real Battery Packs

The amount of current going into and out of the battery pack over time defines the usage. The same current (amp) time history was a applied to our models of NiMH and LiFePO4 to validate real time accuracy for the critical variable of voltage, SOC, and temperature. These are critical to determine performance with the e-motor, and battery pack design.

Figure 22 shows voltage versus time between a simulated and real battery pack. The <1% RMS overall deviation is excellent for drivetrain development. Instantaneous deviations can be attributed to errors in understanding the components in the measured current since it will have battery pack current and generator current. Often times, in order to maintain catalytic converter optimum temperature for minimal emissions, the calibration of the ICE requires running the engine into a generator load that has power wasted into the air conditioning system.

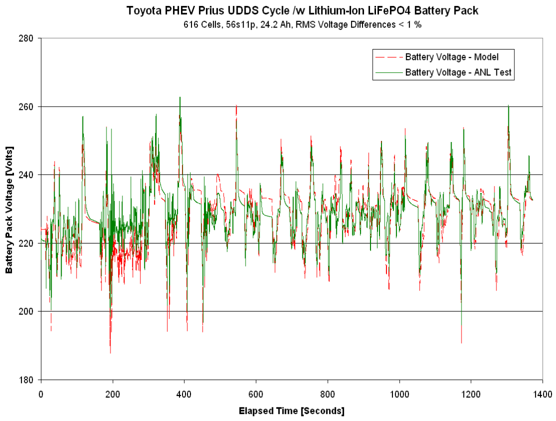


Figure 22

SOC is critical for vehicle performance calibration, battery pack sizing, and BMS validation. Figure 23 plots SOC state between the real and simulated battery.

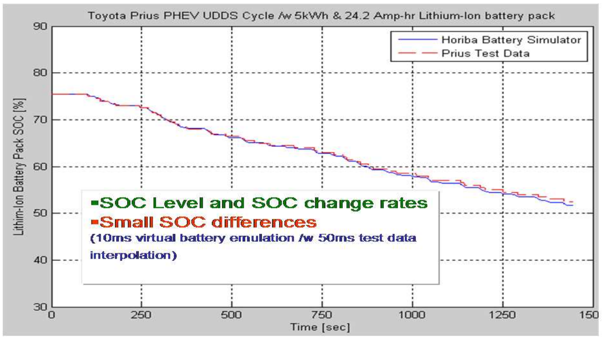


Figure 23: State Of Charge Comparison

Verification of safe operation during any driving ambient temperature condition and vehicle power demand is a paramount concern when integrating large batteries into a vehicle. Adequate prediction of cell and pack temperature will influence pack cooling systems, packaging, and vehicle calibration. The next figure illustrates VB's temperature prediction capability following the same trend as the measured data.

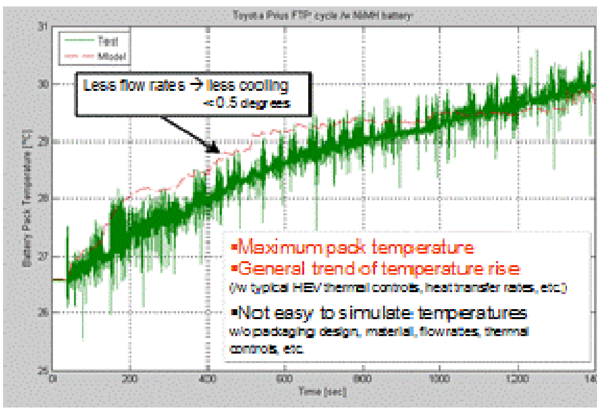


Figure 24: Predicted & Measured Pack Temperature

4 Conclusions

The accuracy and fidelity of VB and VE HIL simulations will allow OEMS to develop electrified powertrains as a parallel activity to engine and battery development. This reduces the time to market for HEV and allow a more precise requirements definition to those designing engine and battery packs.

VB and VE will become quintessential tools to vehicle builders as HEV's seek a 7% to 15%[7] penetration in new vehicle production and is an opportunity for Horiba to offer comprehensive testing solutions. The library of cell chemistries will expand to include Sodium batteries for the heavy duty vehicle and others that show promise in light duty vehicles. Mixed packs of energy and power are currently under software validation starting with Ultra Capacitors.

References

[1] IDtechex,com "Hybrid and Pure Electric Cars 2010-2020" Research Report

[2] Min Chen, IEEE Transactions on Energy Conversion, Vol. 21, NO2 June 2006

[7] Various predictions from research institutes, auto analysts for HEV, PHEV, EV market volume by 2015 as part of total vehicle production in the USA.

Authors

Mr. Newberger has over 25 years of experience in computer aided testing inclusive of real-time digital control system, data acquisition systems, process control systems, simulation systems, and laboratory-wide data integration. He has directed all aspects of product development from concept to system deployment. He holds a BS and MS in Electrical Engineering as well as a minor in Business Administration. He is responsible for supervising the application engineering team when dealing with large powertrain dynamometers systems, multiple powertrain cells, or custom specifications. Additionally his responsibility extends to duties that assure powertrain test products are develop to meet the growing technological demands of powertrain and component testing