

Testing Electrified Drivetrains for Vehicles without the Battery or Engine.

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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 hybrid or 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 cells 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.

Introduction

Historically, the verification, validation & controller calibration of vehicles was brought in from the proving grounds to the laboratory using chassis dynamometer simulating the road. Figure 1 illustrates this concept using HORIBA's automation system (STARS) and dynamometer controller (SPARC). 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 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. 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. 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. Additionally, the torque output of the ICE can be simulated by a real time model of the ICE combustion process and mechanical configuration. 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.

Virtual Engine Capabilities

The engine simulation controls the input dynamometer. Engine simulation provides sensor and data communication inputs to the transmission control unit



Figure 1^[3]

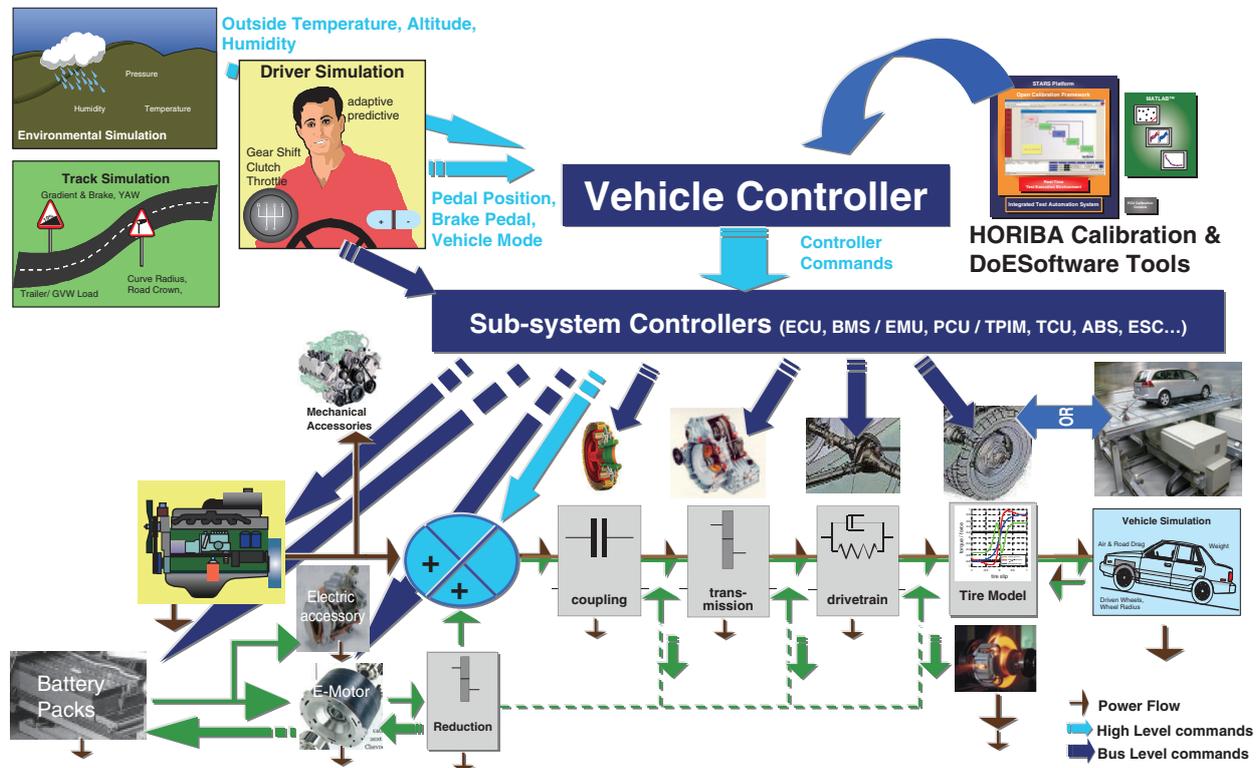


Figure 2

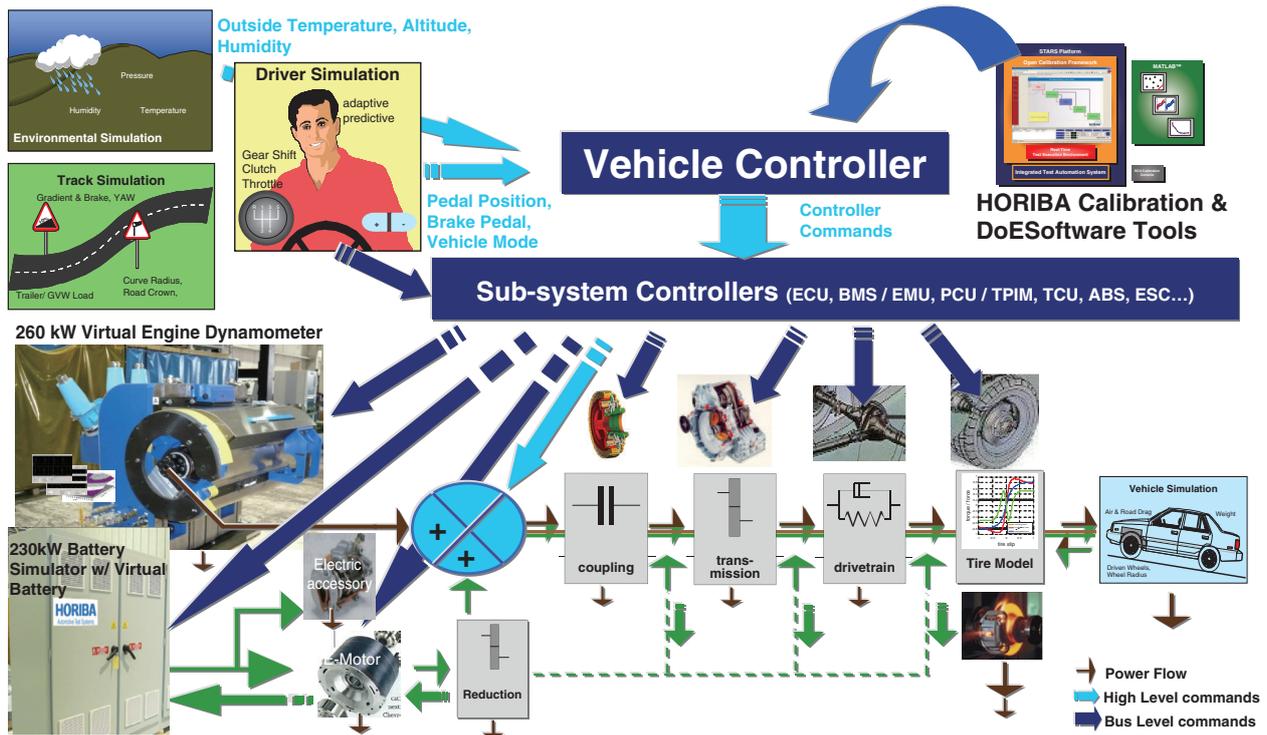


Figure 3 Simulation Diagram: VB & VE in drivetrain test stand (loading dynamometer not shown)

(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.

Engine simulation functions for the transmission input

The engine simulation consists of maps, an engine controller, a parametric model similar to the mechanical 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.

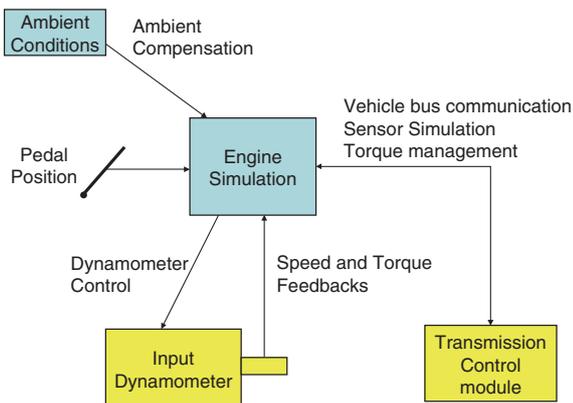


Figure 4

ETPS includes simulation of fuel type (gasoline, diesel) 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. These are characteristic torque signatures of the engine's mechanical configuration.

Maximum Torque Curve of Engine over 2 Crankshaft Revolutions

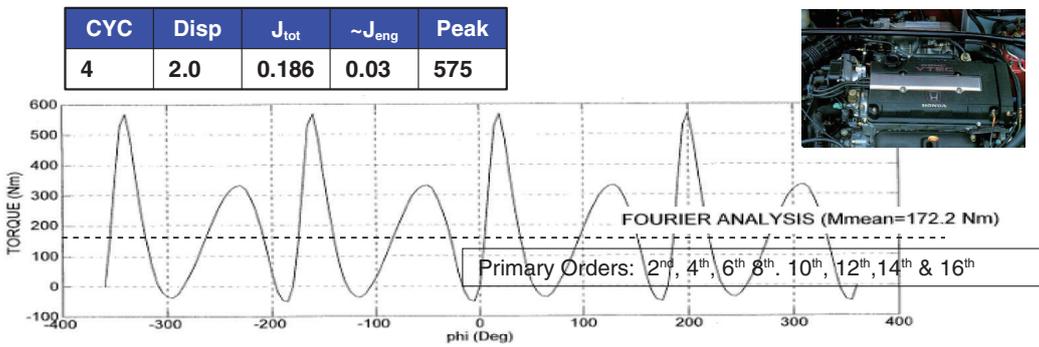
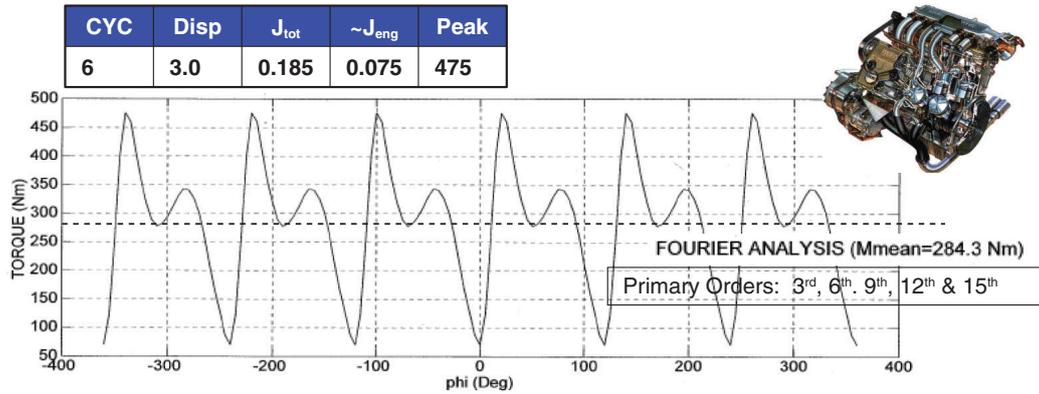


Figure 5

Maximum Torque Curve of Engine over 2 Crankshaft Revolutions

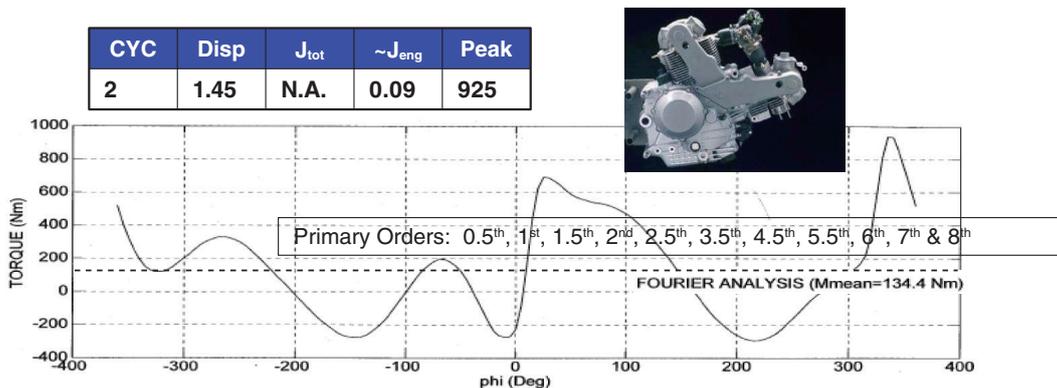
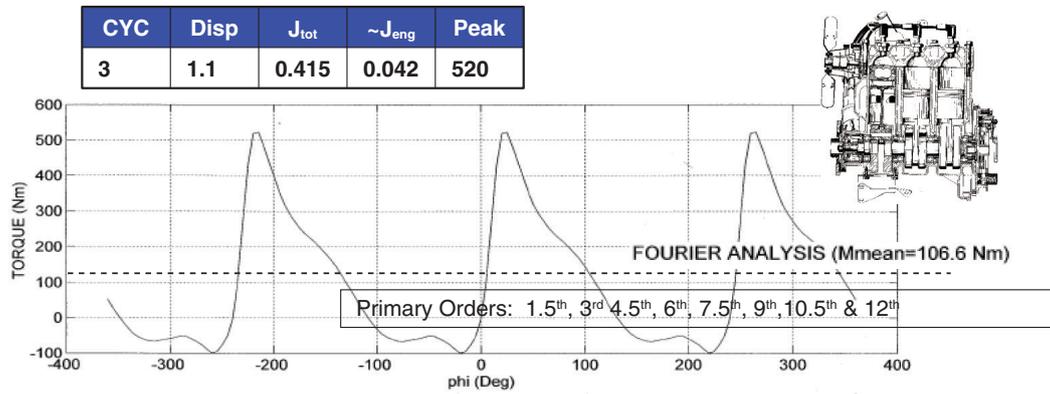


Figure 6

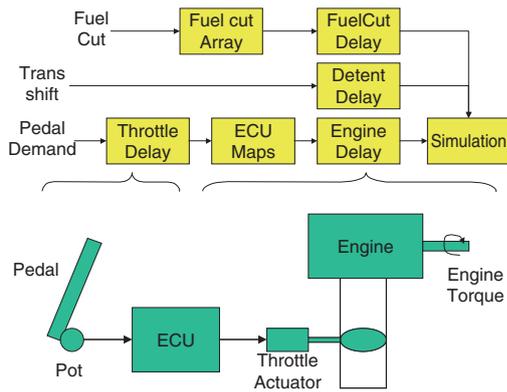


Figure 7

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.

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 provides this capability. 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.

Engine inertia simulation

Drivetrain testing requires that the engine inertia is correct so that the load on the transmission is equivalent

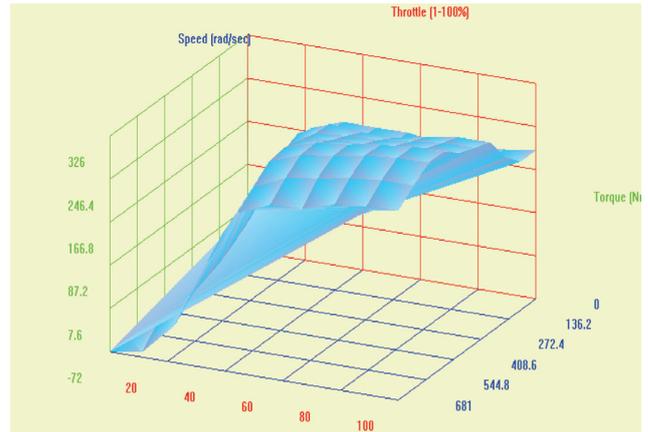


Figure 8

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 being from the torque map simulation.

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

$$= K * T_{eng} + (1 - K) T_{trans}$$

In Figure 9, the VE is run in throttle/speed with the throttle ramped in an attempt to hold the torque relatively

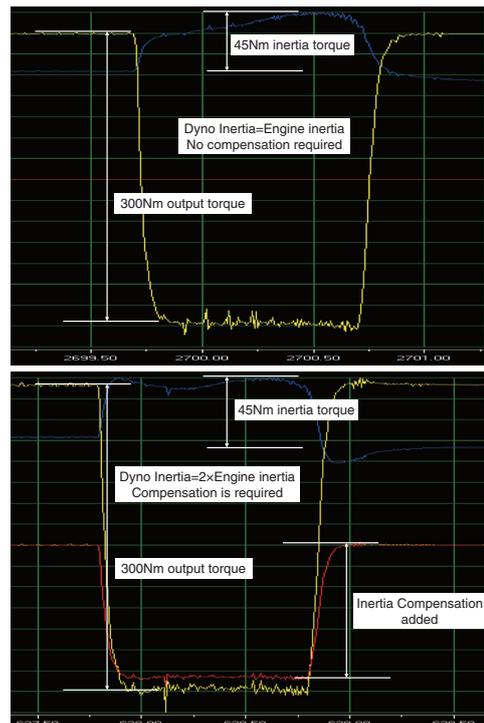


Figure 9