

Test Correlation Framework for Hybrid Electric Vehicle System Model

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ABSTRACT

A hybrid electric vehicle (HEV) system model, which directly simulates vehicle drive cycles with interactions among driver, environment, vehicle hardware and vehicle controls, is a critical CAE tool used through out the product development process to project HEV fuel economy (FE) capabilities. The accuracy of the model is essential and directly influences the HEV hardware designs and technology decisions. This ultimately impacts HEV product content and cost. Therefore, improving HEV system model accuracy and establishing high-level model-test correlation are imperative.

This paper presents a Parameter Diagram (P-Diagram) based model-test correlation framework which covers all areas contributing to potential model simulation vs. vehicle test differences. The paper describes each area in detail and the methods of characterizing the influences as well as the correlation metrics. The paper will also demonstrate how to use this framework as an ongoing test correlation process to continuously track and maintain high confidence of the HEV system model over the course of a given program.

1. INTRODUCTION

HEV Vehicle System simulation is a desktop computer method for directly simulating vehicle drive cycles using a complete model of the HEV propulsion system that represents interactions between driver, environment, vehicle hardware and vehicle controls. A system model of Ford's production powersplit HEV propulsion system is a critical tool used for projection of fuel economy (FE) capability. These projections are used to make critical hardware and technology decisions that determine HEV program content and ultimately impact HEV program cost. Results from the system simulation model are also used to cascade targets to

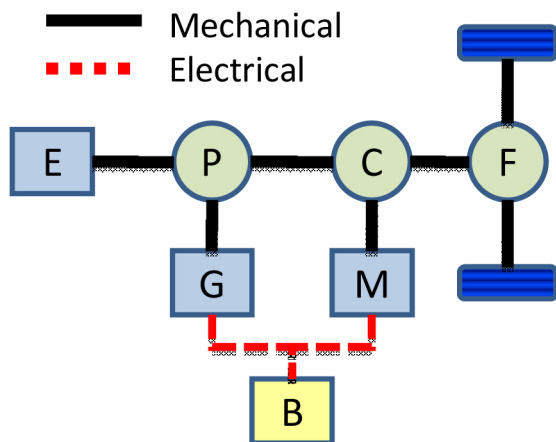
key subsystems and components (e.g. battery, power electronics and electric machines).

Accuracy of the simulation model is critical to development of high confidence FE roadmaps and subsystem/component target cascades for HEV programs. With good system model accuracy, target cascades can be specified with much higher precision, thus avoiding over-design of components to deliver aggressive FE targets. Further, in the later stages of a program, an accurate system model can support vehicle testing for FE attribute development. The model can be used to assess selected vehicle control strategy and calibration changes which can help refine vehicle test plans and improve efficiency of vehicle test efforts.

The powersplit HEV system model used within Ford is implemented in Simulink® using the Vehicle Model Architecture (VMA) standard [1]. Models of each VMA subsystem are stored in libraries and inserted into the architecture for simulation using automated model configuration tools. The system model incorporates submodels for physical and control elements of the vehicle system. For powersplit HEV system simulation, the set of submodels includes a powersplit transaxle subsystem model, a high voltage (HV) electrical subsystem model including high voltage battery and a model of the powersplit vehicle system controller. The system model represents the longitudinal dynamics of the chassis and one-dimensional rotational dynamics of the powertrain system. All mechanical and electrical component losses that have impact on energy usage and fuel consumption are included and distributed across the relevant subsystems. These losses are typically represented by component maps derived from bench/lab tests or high fidelity physical models. Further discussion of Ford's HEV simulation environment and how it is applied to HEV system assessment can be found in [2].

Assessment of vehicle system model accuracy is performed through correlation with vehicle tests. A correlation process framework is described in this paper. This process framework has been applied to development of Ford's production powersplit HEV system. The framework is scoped to the validation of a complete vehicle system model. It's recognized that subsystem/component level model validation is also very important. Throughout the course of developing a HEV system, subsystems/components are characterized in terms of design parameters and behaviors which are then input as parameters to the submodel elements of the vehicle system model. These submodel elements are correlated with subsystem/component tests through separate processes that are outside the scope of this paper. Even with good correlation of individual subsystem/component behaviors, full vehicle system model validation is required. The present paper addresses this problem.

A high level schematic of the powersplit HEV system is shown in Figure 1. The system features two electric machines, a single planetary gear set and a high voltage battery. Full hybrid functionality is possible with the system including: engine start/stop; engine off electric drive; regenerative braking; engine boosting with electric drive. Further, the powersplit system can be operated as an electric CVT when the engine is on. Over a wide operating range, the engine can be controlled to keep its operation within a region of best efficiency in order to minimize fuel consumption.



B – Battery G – Generator
C – Counter Gear E – Engine
F – Final Drive M – Traction Motor
P – Planetary Gear

Figure 1. Schematic of the powersplit HEV system.

2. FRAMEWORK AND METHODOLOGY OVERVIEW

A Parameter Diagram (P-Diagram) framework is used to define the vehicle simulation-to-test correlation methodology as depicted in Figure 2 [3]. At the center of the P-Diagram is the Correlation Process. The main process inputs are selected sets of signals from simulation and test results on which the correlation is to be based. The Ideal Process Output to be achieved is that a selected set of critical quantities from the simulation results fall within the range of test-to-test variation. Conversely, the main error state is critical quantities fall outside the range of test-to-test variation. Further discussion of the exact quantities to be used for comparison is given later in the paper.

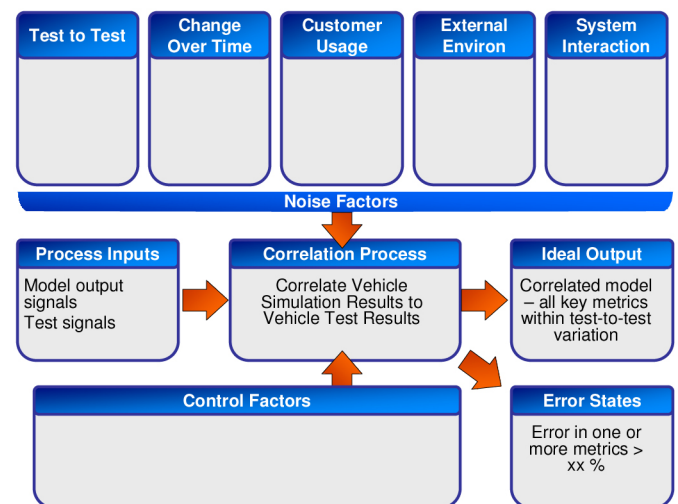


Figure 2. P-Diagram framework for Hybrid Electric Vehicle simulation-to-test correlation.

The approach to realizing a Correlation Process that achieves the Ideal Process Output consists of the following elements:

1. Choosing a set of valid vehicle tests for comparison with simulation
2. Defining:
 - a. Quantities and signals for simulation-to-test comparison
 - b. Metrics for indicating level of correlation between simulation and test
3. Comparing simulation and test results based on:
 - a. Energy analysis
 - b. Statistical analysis
 - c. Signal trace analysis
4. Identifying and fixing root causes for significant discrepancies between simulation and test by:

- a. Reducing/eliminating noise factors
- b. Improving control factors

The following main sections cover each of these areas in more detail.

3. VEHICLE TEST REQUIREMENTS

A foundational element of the correlation methodology is that simulation-to-test comparisons are based upon a set of repeated vehicle tests. Simulation correlation is judged within the context of the distribution of test results given that test results will vary based on a number of noise factors. Critical requirements for the selected set of vehicle tests are summarized in the following paragraphs.

Test Type - Since the main objective is to correlate FE simulation results, the type of vehicle test should be a standard regulatory test for measuring vehicle fuel economy conducted in an appropriate facility. For North American vehicles, this would be one or more of the EPA five cycle tests [4]. Depending on the capabilities of the vehicle simulation model and which aspects are to be validated, correlation can be separated according to the main effects present in each of the cycles. For normal vehicle operation under fully warmed up conditions, the hot EPA City and Highway cycle tests provide a good starting point for model correlation efforts.

Vehicle Configuration - Tracking the hybrid vehicle configuration throughout the course of a vehicle program can be challenging as work progresses through vehicle prototype stages towards production. Software strategy, software calibration and, in some instances, even hardware changes can happen. An important criteria for selecting a set of vehicle tests for simulation correlation is that the hardware and software elements that define the vehicle configuration should be fully known and the same for the entire set of tests. 'Fully known' means:

- **Hardware** - Critical propulsion system hardware components have been properly characterized through appropriate bench/lab tests to create the parameter data required by the system simulation model for the hardware in the vehicle. Critical components include engine, transaxle, electric machines, power electronics (including high-to-low voltage DC/DC converter), traction battery and other miscellaneous driveline components (CV joints, bearings, etc).
- **Software** - Software code and calibrations should be available and fully traceable to the set of vehicle tests to be used for simulation correlation work. Typically these are held in a repository over the course of a vehicle program. The main challenge becomes maintaining traceability to vehicle tests.

Vehicle Pre-conditioning - The vehicle must be properly pre-conditioned for the selected set of correlation tests. For HEV's, the important elements of proper pre-conditioning include:

- **Soak** - The vehicle must be soaked for an appropriate length of time at the conditions prescribed by the test.
- **HV Battery Condition** - The high voltage battery state-of-charge (SOC) and state-of-health must be representative of conditions that are represented by the simulation model. Battery SOC should be within a valid operating range and the battery condition should be within the life range represented by the simulation model.
- **LV Battery condition** - The low voltage battery should also have been properly conditioned for the test. The battery should be fully charged to avoid excessive charging during the test which can skew fuel economy results.

Balanced SOC - For the tests selected, the HV battery SOC should be balanced over the drive cycle within tolerances dictated by the regulatory test. SOC behavior that deviates from this constraint indicates an invalid test for determining fuel economy.

Vehicle Speed Trace - For a valid fuel economy test on a given regulatory cycle, the actual vehicle speed trace must match the target speed trace within a given tolerance.

Driver/Driving Style - HEV propulsion system energy usage is known to be sensitive to driver behavior [5, 6]. A valid set of tests for correlation should have been executed by the same test driver using a consistent driving style.

Instrumentation/Data Acquisition - Selected vehicle tests must have a complete measured data set featuring critical signals and quantities necessary for a complete energy analysis (see Section 4) and comparison with critical primary signals (e.g. torques, speeds, etc.) from corresponding vehicle simulations. One signal that is particularly desirable from an energy analysis standpoint is the wheel torque. Direct measurement of wheel torque using properly calibrated wheel torque or half shaft torque meters is highly desirable, but not always possible. In the absence of such measurements, a method for inferring wheel torque has been developed as part of the current work. This is described further in Section 7.

4. CRITICAL QUANTITIES & SIGNALS

Critical quantities and signals to be used for comparison of vehicle simulation and test results are summarized in [Tables 1](#) and [2](#). These are organized according to vehicle subsystem and appropriate units are given.

[Table 1](#) summarizes cycle averaged and integrated quantities that are important for verifying good simulation-to-test

correlation. These quantities include measures of energy usage by critical components (e.g. engine work) as well as indicators of the behaviors of the vehicle control strategy with respect to power and energy management. The latter include number of engine starts/stops, engine on time and delta SOC over the cycle.

Table 2 summarizes time varying vehicle response signals that are important to compare for assessing correlation between test and simulation. Second by second traces of these signals from simulation and test can be overlaid to understand differences in detailed behaviors and responses. An additional requirement (in addition to those given in Section 3) for selected correlation vehicle tests is that the signals listed in Table 2 be available as part of the data acquired from the tests. There are several torques specified in the table which are not measured directly in vehicle tests. Control command and estimated feedback signals indicating engine, generator and motor torques are available on the CAN network. As mentioned above, wheel torque can be measured with appropriate instrumentation, however, in the absence of direct measurement, a method for inferring wheel torque from other information is outlined in Section 7.

Table 1. Cycle averaged and integrated quantities used for vehicle simulation-to-test correlation.

Subsystem	Quantity	Units
Powerplant	Engine Work	kJ
	Engine on time	s
	Engine operating efficiency	%
	Number of engine starts/stops	-
	Fuel consumption	g
Electrical	HV battery energy	kJ
	HV battery delta SOC over cycle	%
Transmission	Generator mechanical work	kJ
	Motor mechanical work	kJ
	Motor electrical work during engine off periods	kJ
	Motor operating efficiency during engine off periods	%
Chassis	Wheel work	kJ

Table 2. Time varying signals used for vehicle simulation-to-test correlation.

Subsystem	Quantity	Units
Powerplant	Engine speed	Rpm
	Engine torque	N-m
Electrical	HV battery current	A
	HV battery voltage	V
	HV battery SOC	%
	Accessory load current	A
	Accessory load voltage	V
Transmission	Generator speed	Rpm
	Generator torque	N-m
	Motor speed	Rpm
	Motor torque	N-m
Chassis	Vehicle speed	kph
	Wheel speed	Rpm
	Wheel torque	N-m

5. METRICS FOR CORRELATION

Selecting an appropriate set of metrics is important for quantitatively determining the level of correlation between a simulation result and a set of tests. Appropriate metrics should be based on a statistical analysis approach in order to determine where simulation results fall within the distribution of test results given that test results will vary based on a number of noise factors. For cycle averaged and integrated quantities, simulation results can be compared with the mean of the corresponding quantities from the set of selected tests. The percent deviation of the simulation result from the test mean is used as a key metric for correlation. Also, the test standard deviation for each quantity can be computed and further used to calculate the number of standard deviations the corresponding simulation result is from the test mean. This metric gives a direct indication of how a simulation result compares with the range of test results that are possible and most probable.

As described in the previous section, the correlation approach outlined in the present paper also involves comparing second-by-second time varying signal traces between test and simulation. To establish a single metric indicating the level of correlation between any two signal traces, the normalized cross correlation power (NCCP) is used:

$$NCCP = \frac{\max[R_{xy}(\tau)]}{\max[R_{xx}(\tau), R_{yy}(\tau)]}$$

$$R_{xy}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t) \cdot y(t - \tau) dt$$
(1)