PHEV Hymotion Prius Model Validation and Control Improvements

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Abstract

Argonne National Laboratory, working with the FreedomCAR and Fuels Partnership, maintains vehicle simulation software: the Powertrain System Analysis Toolkit (PSAT). Because of the importance of component models and the complexity involved in setting up optimized control strategies, the models and controls developed in PSAT require validation. The highly instrumented Toyota Prius, including engine and half-shaft torque sensors, was tested in Argonne's Advanced Powertrain Research Facilities (APRF) both in its original configuration and with the Hymotion L5 plug-in hybrid electric vehicle (PHEV) battery pack to provide the data needed for a thorough comparison of model results and test data. This paper first describes the vehicle test results and explains the validation process on the basis of an analysis of the differences between the test and simulation results. Then it demonstrates the validation of the PHEV Hymotion Prius. Finally it assesses the impact of different control strategy options for the PHEV.

Keywords: plug-in, hybrid, modeling, validation, control strategy

1. Introduction

Plug-in Hybrid Electric Vehicles (PHEV) is a promising alternative to conventional gas-powered vehicles. As the energy storage system can be recharged using an outside plug, their battery can be depleted allowing significant fuel displacement.

Because the set of conceivable hybrid electric vehicle (HEV) powertrains is so large, it is impractical to perform an exhaustive search that uses fabrication and testing of prototypes to provide information on the ideal powertrain for a given application. Instead, a simulation tool should be used to provide guidance of similar quality, assuming that the models accurately predict the behavior of the powertrains under investigation. The simulation tool used here to develop the vehicle model is the Powertrain System Analysis Toolkit (PSAT), a state-of-the-art, flexible, reusable simulation package developed by Argonne National Laboratory (Argonne). PSAT [1, 2] is designed to serve as a single tool that can be used to meet automotive engineering requirements throughout the development process, from modeling to control. One of the most important characteristics of PSAT is that it is a forward-looking model; it allows users to model real-world conditions by using real commands. For this reason, PSAT is called a command-based or driver-driven model. Written in Matlab/Simulink/Stateflow [3], the software allows the simulation of a wide range of vehicle applications, including light- (two- and four-wheel-drive), medium-, and heavy-duty vehicles. In 2004, PSAT, the primary vehicle simulation tool supporting FreedomCAR and the Vehicle Technologies Program [4], received an R&D 100 Award, which highlights the 100 best products and technologies from around the world newly available for commercial use.

The Advanced Powertrain Research Facility (APRF) at Argonne handles U.S. Department of Energy (DOE) technology validation and benchmark testing of advanced vehicle technologies. Argonne tests new HEVs and plug-in HEVs (PHEVs) to provide data that are used to update PSAT. The data are also used to provide DOE and auto industry engineers with benchmark specifications that aid in forecasting future technology developments.

To verify the accuracy of a PSAT model, the outputs predicted by the component and powertrain models need to be compared to test data, a process referred to here as "validation." This paper describes the steps used to validate the Hymotion L5 PHEV model by using test data measured at Argonne's APRF.

2. Vehicle Testing

2.1 Vehicle Description

The Hymotion PHEV Prius, shown in Figure 1, contains a supplemental Li-ion battery pack to provide an additional 5 kWh of electrical energy storage [5]. This system includes a control system to enable the Prius to operate in a charge depleting (CD) mode. Controller area network (CAN) communication is used to communicate with the production Prius powertrain controller and operate the vehicle in electric vehicle (EV) mode at speeds of up to 40 miles per hour (mph) or until a power requirement threshold is exceeded. As a result, the powertrain primarily uses electrical energy during urban driving, which minimizes engine operation and thus reduces fuel consumption. This vehicle does not have a true all electric range (AER) because of the engine operation requirements, but it is a good representation of a near-term PHEV.

Figure 1: Hymotion PHEV Prius on Chassis Dynamometer with Hymotion 5-kWh Battery System Installed in Parallel to the Production Battery

Before the installation of the Hymotion battery system, the Toyota Prius was tested extensively as a production HEV at Argonne by using the dynamometer coefficients of the 2004 production Prius. For direct comparison, the same coefficients were used for the Hymotion PHEV testing, but since the Hymotion battery system weighs 73 kg, the test weight was increased to 1,546 kg. The dynamometer coefficients used for the Hymotion PHEV Prius testing are shown in Table 1.

Table 1: PHEV Prius Dynamometer Coefficients

Coefficients	A	B	C
Target	19.918	0.1393	0.0164
Dyno Set	3.604	-0.1538	0.0179

For the PHEV Prius testing, a 32-channel National Instruments PXI chassis was used to collect the signals from the in-vehicle sensors and the dynamometer and test cell sensors. A Hioki "HiTESTER" was used to measure the current and voltage of both onboard battery systems and to integrate amp-hours (Ah) and kilowatt-hours (kWh). A CAN bus to universal serial bus (USB) communication device was used to read and record parameters from the vehicle CAN bus that are used by the powertrain engine control unit (ECU), as well as parameters from the Hymotion controller (such as state of charge [SOC] and various temperatures). An on-board diagnostic (OBD) scan tool was also used to read and record other communication parameters from the vehicle CAN bus used by the Prius powertrain and battery ECU.

To properly evaluate the CD characteristics and the amount of petroleum displacement of a PHEV, the vehicle was tested through the full discharge range of the pack by running repeated urban dynamometer driving schedule (UDDS) cycles until the charge-sustaining (CS) operation was entered and the battery SOC was charge-balanced over an entire drive cycle. The plug-in battery pack was recharged overnight to prepare for more testing the following day.

2.2 Test Results on UDDS

Beginning from a cold start, the PHEV Prius was tested on consecutive UDDS cycles. The battery energy was depleted through the second hill of the fourth consecutive UDDS. In total, 25 miles were driven in CD mode. During those cycles, the powertrain is primarily operated using the battery energy, except above 40 mph or when the EV mode power threshold was exceeded. After the repeated UDDS cycles were completed, 4.3 kWh of AC energy was measured to fully recharge the battery pack. This charging event took approximately 6 hours. Because 3.2 kWh of DC energy was used over the UDDS cycles, the overall charging efficiency was approximately 75%. Table 2 shows the unadjusted results from the five consecutive UDDS cycles.

Figure 2 shows the consecutive UDDS cycles. The red dots on the graph indicate when the engine is operating and consuming fuel. Note the accumulated fuel consumed is much lower for the Hymotion CD PHEV Prius (PHEV) than the stock CS Prius. After the vehicle fully depletes the usable battery energy, it operates in the standard CS mode, just as a production Prius operates.

Table 2: Hymotion Prius, Consecutive UDDS Results

UDDS	#1	#2	#3	#4	#5
Miles Driven (mi)	7.48	7.48	7.48	7.48	7.47
Fuel Used (gal)	0.051	0.037	0.040	0.101	0.113
Electrical Energy Consumed (DC kWh)	0.93	0.96	0.94	0.23	-0.12
Fuel Economy (mpg)	148	200	187	74.3	66.4
Electrical Consumption (DC Wh/mi)	123	128	125	30.6	15.9

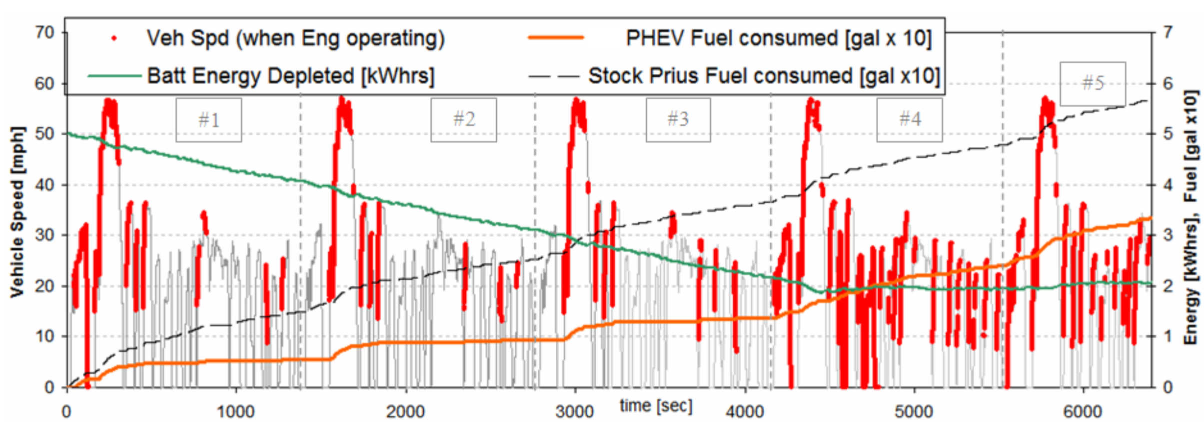

Figure 2: Hymotion Prius Driven on Repeated UDDS Cycles;
Cold Start from 100% SOC to CS Operation

3. Validation Process

To properly validate a model, several key parameters need to be measured. For advanced vehicles such as power split vehicles, it is necessary to measure the torque of several components. Argonne has been conducting very extensive testing of advanced vehicles, in terms of both instrumentation [6] and number of tests.

Because of the large amount of data, a generic process [7] is necessary to automatically generate reports that will allow engineers to quickly analyze data quality. This process, as shown in Figure 3, is based on five steps:

1. Automatically realign the data when different sources are used (e.g., emission bench, dynamometer).
2. Select the proper sensor when the same parameter can be measured/recorded from different sources.
3. Quantify the uncertainty of each sensor by comparing its values with measured or calculated parameters by using powertrain equations.
4. Reuse existing post-processing capabilities developed initially for simulation purposes to automatically calculate effort, flow, power, energy, and efficiencies, as well as use the analytical tools already available in PSAT.
5. Automate report generation so that complete analysis can be summarized in an HTML document within minutes.

Data post-processing usually includes filtering and merging sensors with different sample times. Because these tasks were performed in the vehicle test facility, these functionalities were not implemented in the process described in this paper.

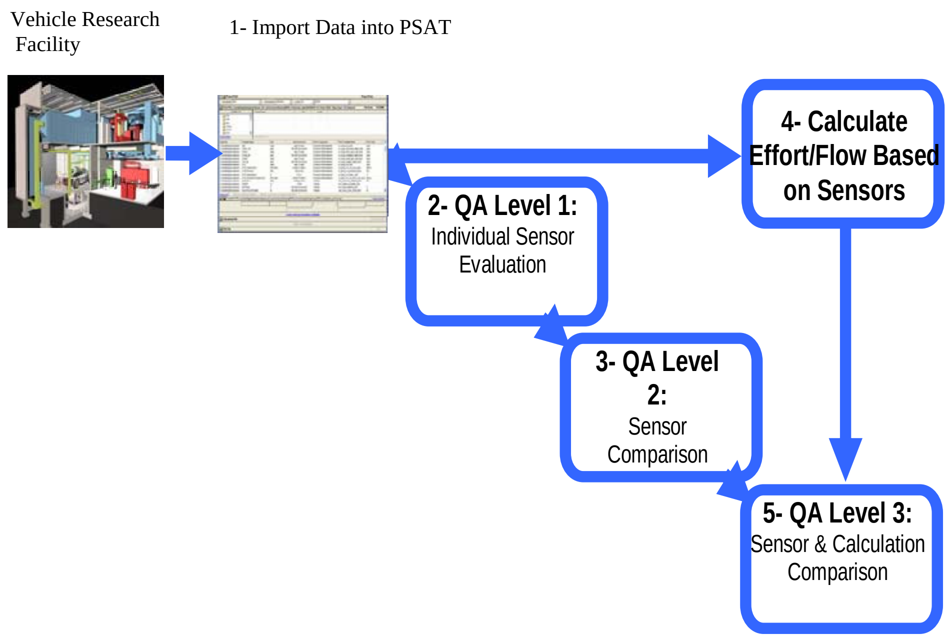

Figure 3: Generic Data Quality Analysis Process

4. Hymotion Prius Validation

The first step in the validation process consists of matching the component operating conditions, such as engine ON/OFF, torque, and speed. Once each component operates according to the tests, the values for fuel economy and electrical consumption should match the test data, pending component data accuracy. The 2004 Prius HEV model was validated on the basis of component data provided by Oak Ridge National Laboratory (electric machine and boost converter), Idaho National Laboratory (battery), and Argonne (engine and vehicle). The performance characteristics of the additional components of the Hymotion PHEV Prius (battery and power electronics) were estimated on the basis of component experts' inputs. The battery model was developed by Argonne's battery group to represent similar Li-ion technology [8].

The validation was performed on both UDDS and highway fuel economy test (HWFET, i.e., highway cycle) drive cycles. However, only the UDDS cycle data are presented in this paper cycle showed the most differences when compared with the HEV Prius. Figure 4 shows the comparison between test and simulated engine torque. Because Hymotion vehicle controller is unknown and the impact of the driver, it is difficult to exactly reproduce every engine ON/OFF event. Except for the first and last events, all engine ON/OFF events are reproduced in the simulation.

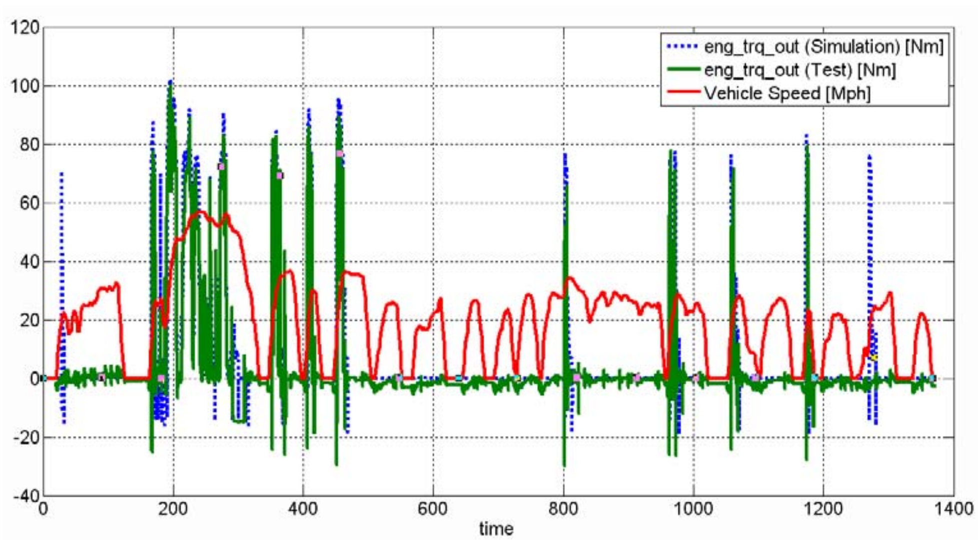

Figure 4: Engine Torque Comparison (UDDS during CD Mode)

Figure 5 shows the engine torque comparison on the second hill of the UDDS, showing good correlation with the test data.

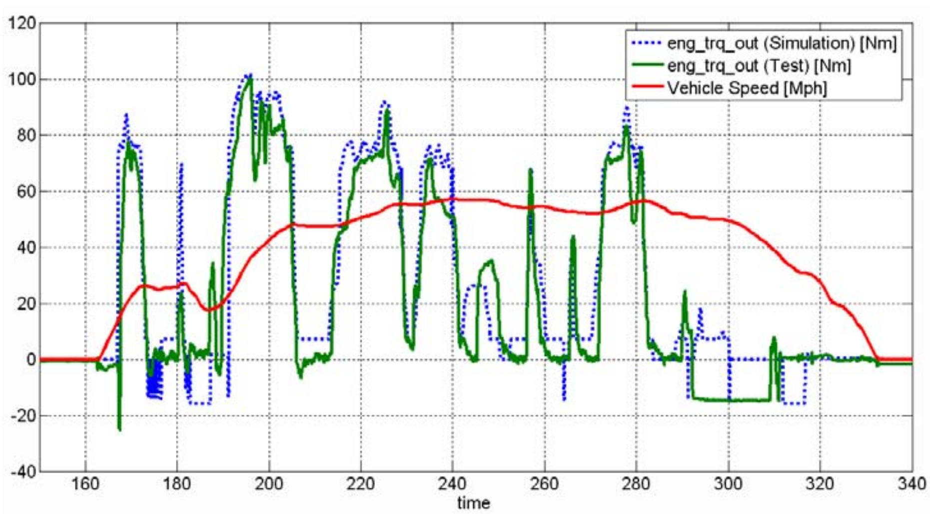

Figure 5: Engine Torque Comparison (UDDS during CD Mode) – ZOOM

Figure 6 shows the power of the high-capacity battery during a portion of the UDDS. Note that the battery does not take part in the regenerative events.

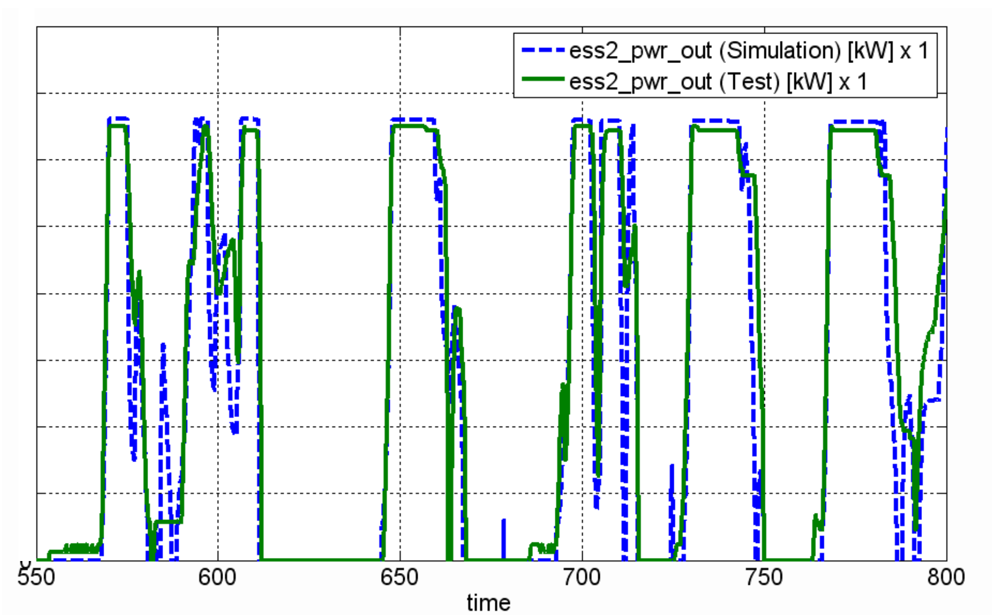

Figure 6: High-Capacity Battery Power Comparison (UDDS during CD Mode)

Tables 3 and 4 summarize the main results of the test and simulation for both CD and CS modes. Both fuel and electrical consumption demonstrate good correlation with the test data.

Table 3: Validation Results – UDDS during CD Mode (Test # 60610104)

Parameter	Units	Test	Simulation	Absolute Difference	Relative Difference
Fuel Consumption	l/100 km	1.33	1.22	0.11	8.8%
Elec. Consumption	Wh/km	86.3	83.8	2.5	2.8%
SOC Initial	%	62	62	0	0
SOC Final	%	62	62.8	0.8	1.3%

Table 4: Validation Results – UDDS during CS Mode (Test # 60610106)

Parameter	Units	Test	Simulation	Absolute Difference	Relative Difference
Fuel Consumption	l/100 km	3.64	3.58	0.06	1.7%
SOC Initial	%	62	62	0	0
SOC Final	%	62	61.8	0.2	0.3%

5. Control Strategy Improvements

When analyzing the Hymotion control strategy, one notices that the engine average efficiency is lower in CD mode than in CS mode, respectively 30.1% to 33.5%. This significant difference is due to the large amount of fuel that is consumed at low power, as shown in Figure 7.

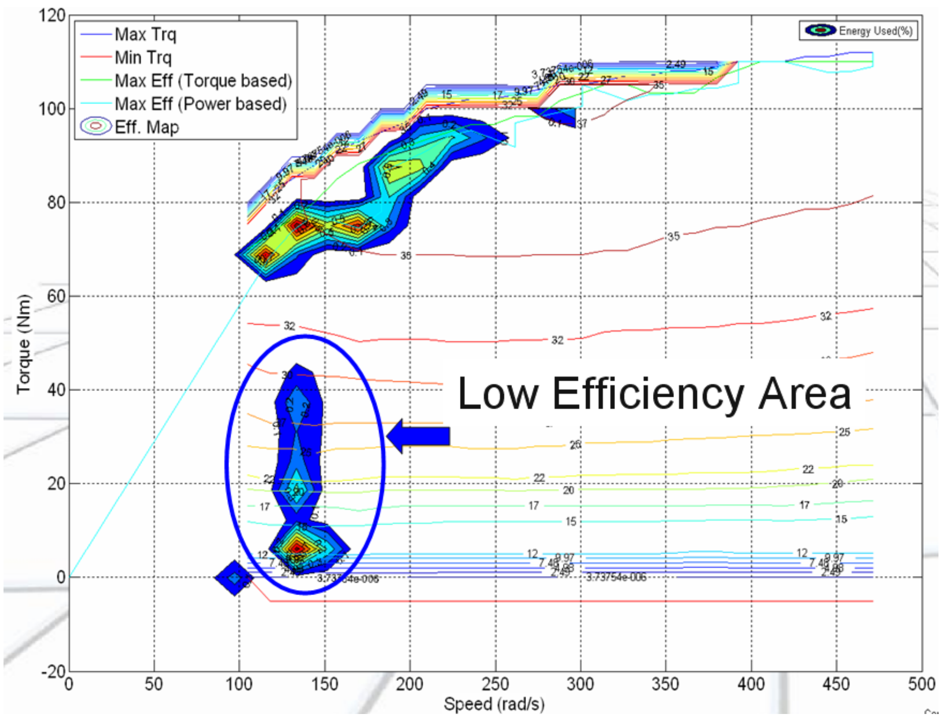

Figure 7: Engine Operating Conditions
Density = f(Energy) – (UDDS during CD) – Simulation

Two control strategy changes were considered to improve the average engine efficiency during the cycle:

1. Minimize the number of engine ON/OFF events.
2. Operate the engine closer to its best efficiency curve.

5.1 Engine ON/OFF Reduction

As shown in Figure 8, several engine ON events occur at times of low vehicle-power demand during the UDDS drive cycle. By changing some control parameters, such as the minimum power required at the wheel to start the engine and the constraints of the power supply of the high-capacity battery, these engine ON events can be deleted.

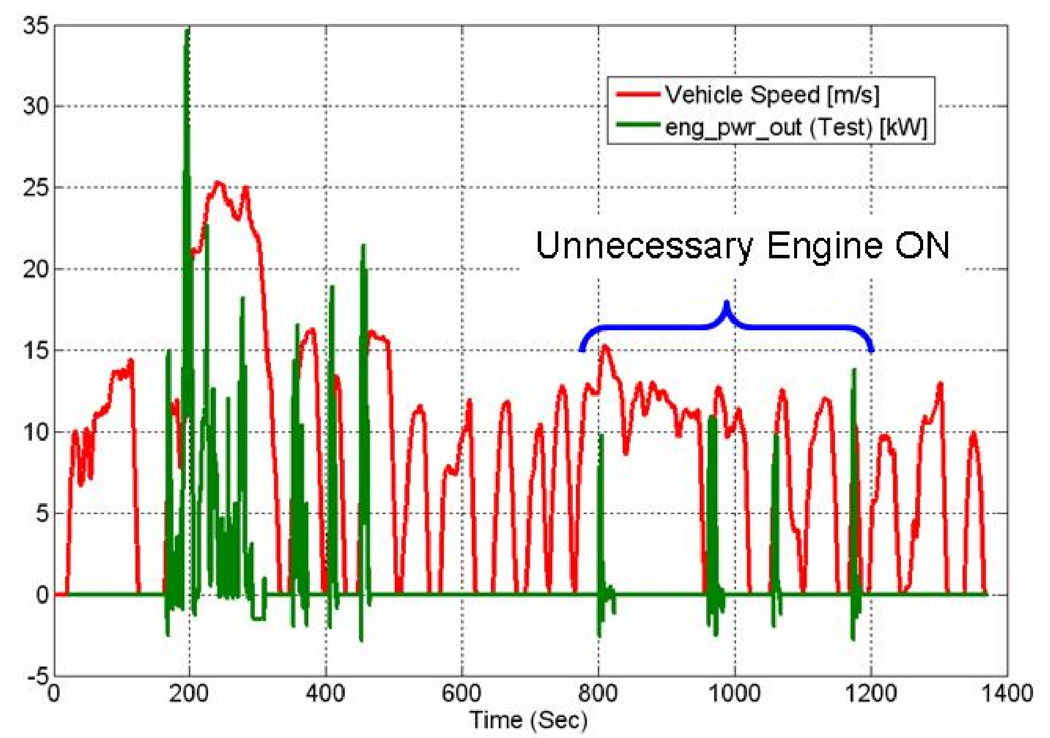

Figure 8: Engine ON/OFF Modification (UDDS during CD Mode)

As a consequence, the amount of fuel consumed in the low efficiency area decreases, as shown in Figure 9. However, the engine still operates at low power, even when an engine ON event is required because of high power demand or vehicle speed.

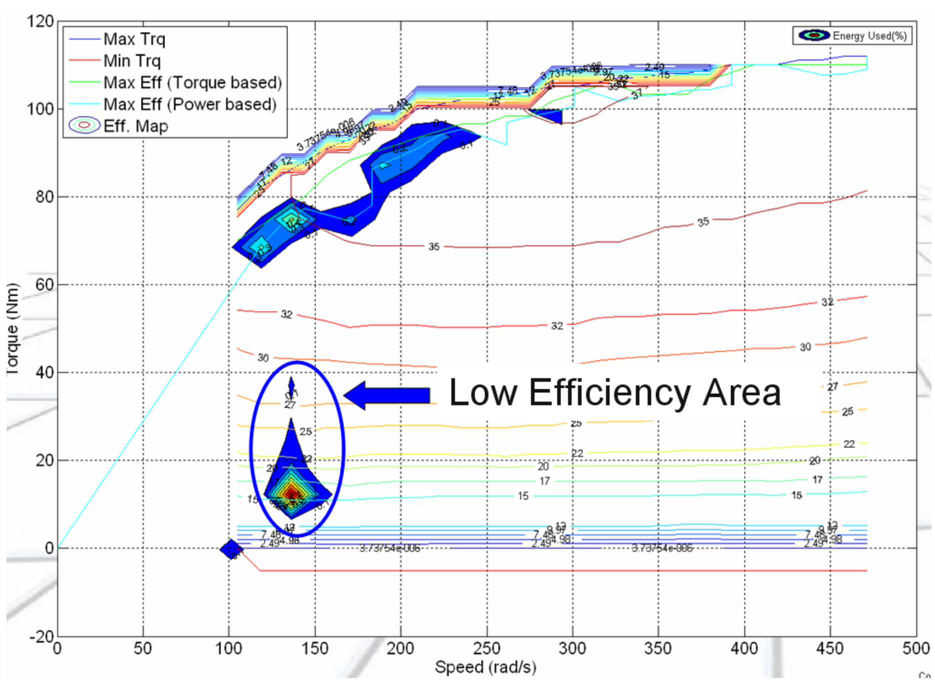

Figure 9: Engine Operating Conditions after Engine ON/OFF Modification: Density = f(Energy) – (UDDS during CD Mode)

Figure 10 shows electrical consumption as a function of fuel economy for the reference control (from both the test and simulation) as well as the modified control. Note that the relationship between both energies remains unchanged.

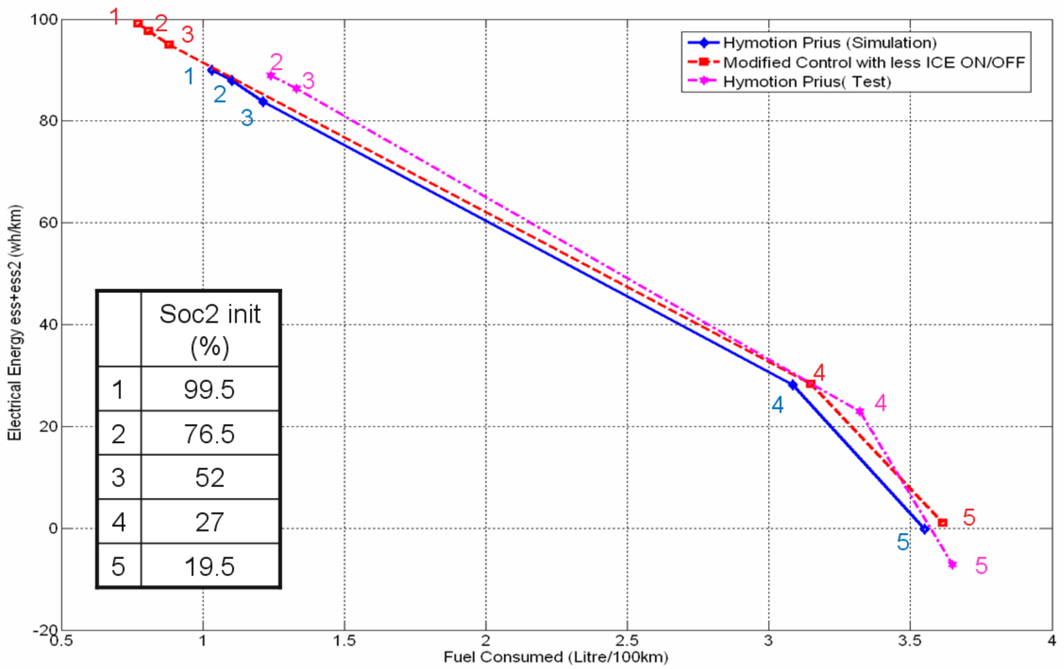

Figure 10: Energy Consumption Change Due to Fewer Engine ON/OFF Events (UDDS)

5.2 Engine Operating Condition Improvement

In addition to the engine ON/OFF event logic modifications, we also changed the engine operating conditions during CD. As can be seen in Figure 11, the Hymotion Prius engine operates at lower power during the second hill of the UDDS than does the Prius HEV. As a result, there is a drop in engine efficiency.

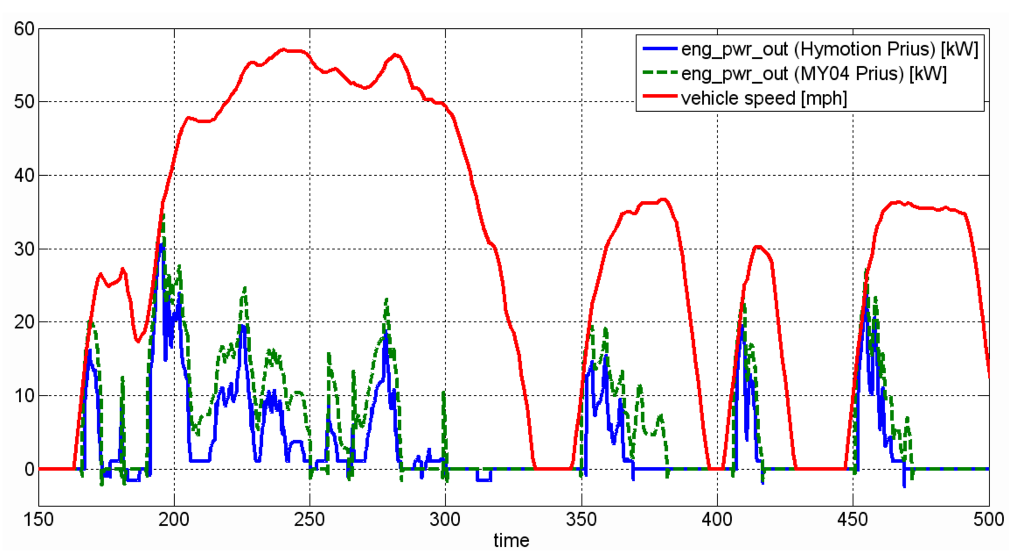

Figure 11: Engine Power Comparison between Hymotion and Reference Prius (UDDS)

Figure 12 shows the engine power for both the HEV and the Hymotion Prius after control modification, showing a good correlation. The control logic algorithm has been modified.

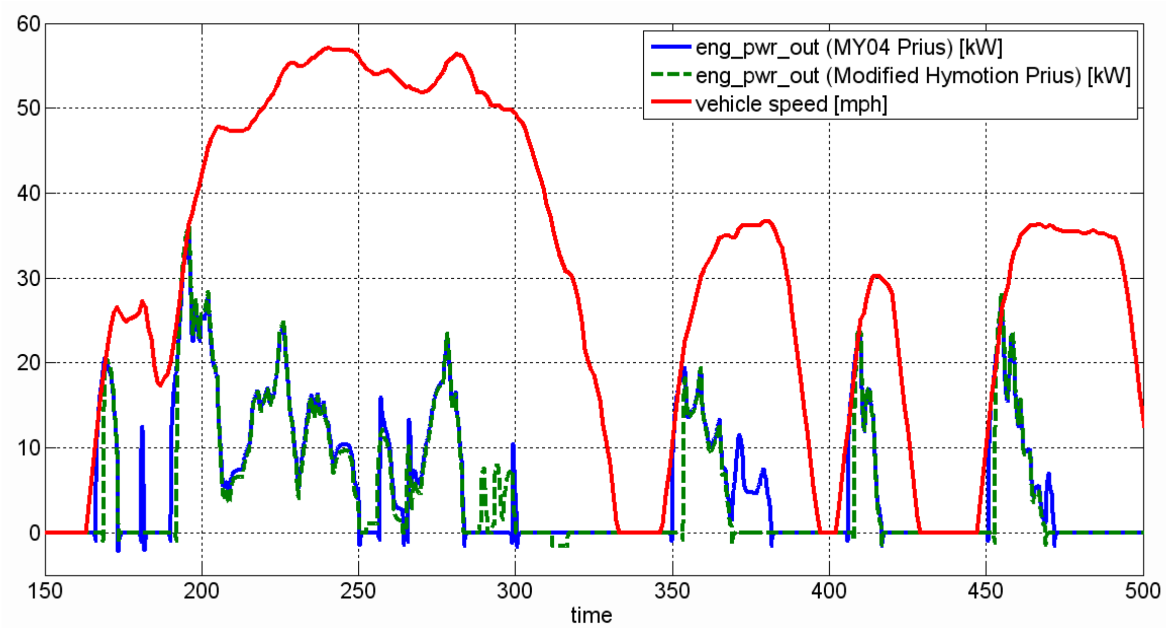

Figure 12: Engine Power Comparison after PHEV Control Modification (UDDS)

The amount of fuel consumed in the area of low efficiency has now almost disappeared, as shown in Figure 13.

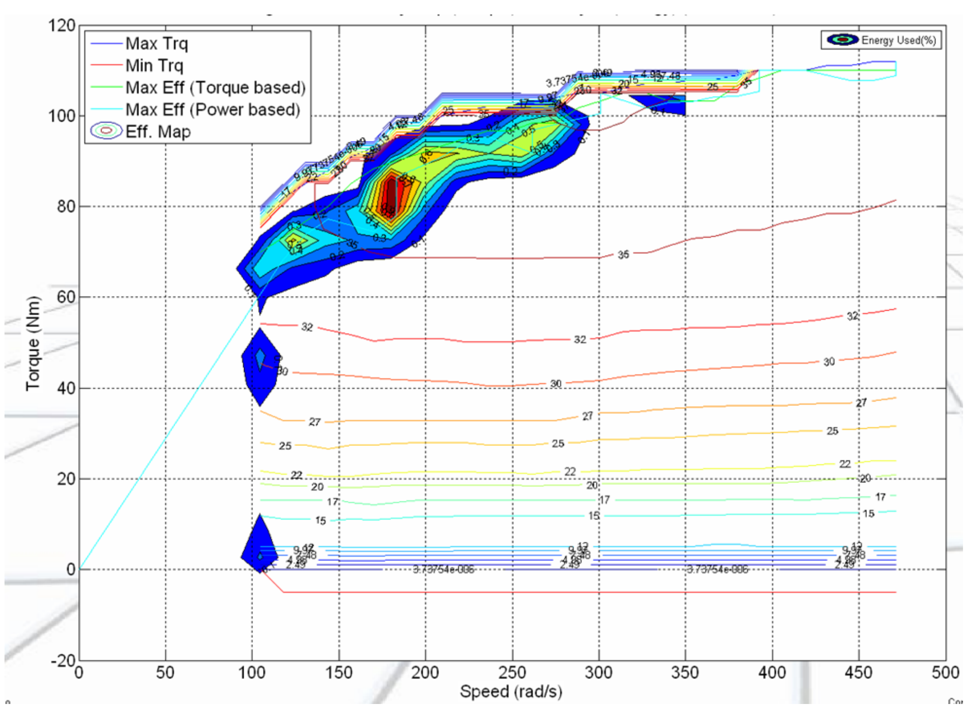

Figure 13: Engine Operating Conditions after Engine ON/OFF and Power Modifications: Density = f(Energy) – (UDDS during CD Mode)

Figure 14 shows electrical consumption as a function of fuel economy for the reference control (from both the test and simulation) as well as both modified controls. Note that the relationship between both energies is now changed when the engine operates at higher power. The slope of the control based on the higher engine power is not as stiff as the other slope. This is due to the fact that the engine is used to recharge the battery. This approach is consistent to the one used in previous studies [9] based on global optimization, which demonstrated that the engine, when ON, should operate close to its best efficiency curve.

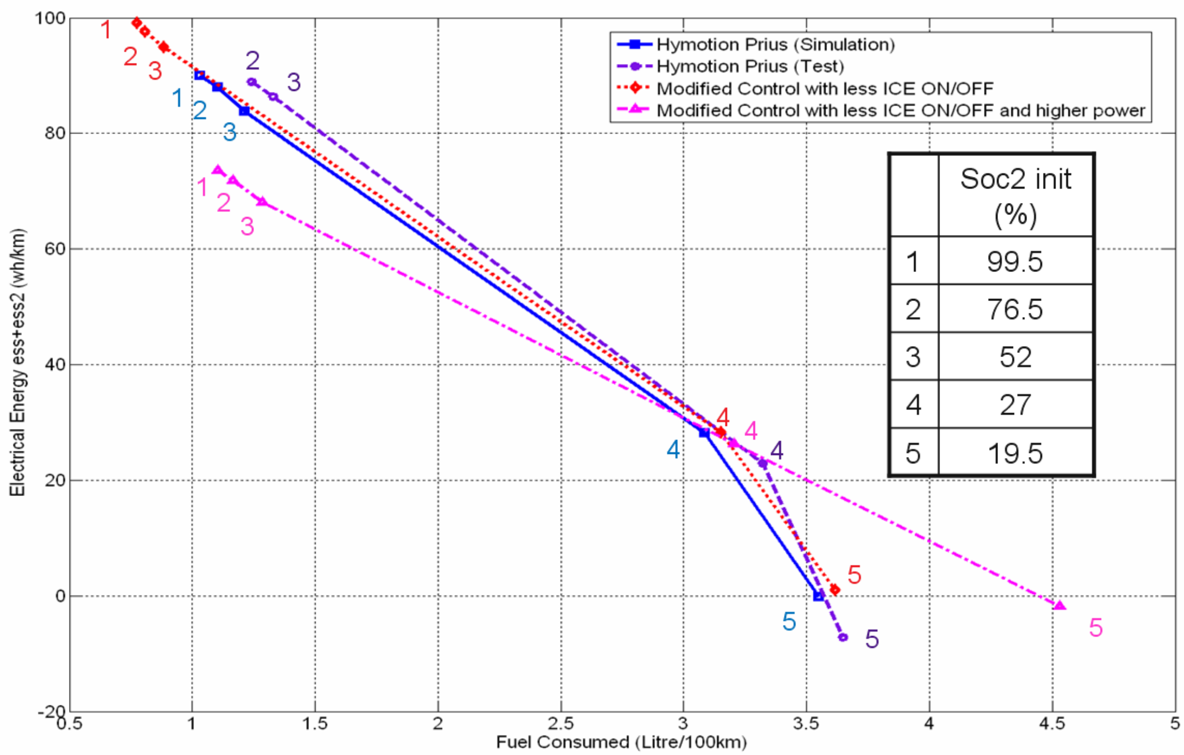

Figure 14: Energy Consumption Change Due to Control (UDDS)

5.3 Control Strategy Options Comparison

Figure 15 shows the amount of fuel consumed after driving six UDDS cycles in a row as a function of distance for the reference HEV Prius and the PHEV Hymotion with original and modified control. As expected, using a PHEV allows a significant reduction in fuel consumption compared to that of the Prius HEV. Once the PHEV reaches CS mode (i.e., 35 km for the modified control strategy with minimum engine ON), the slope of the fuel consumed becomes identical to that of the reference HEV vehicle.

As shown in previous studies [10], the optimum control for PHEVs depends highly on the distance traveled. When someone is driving a short distance, he or she would like to use the battery as much as possible to minimize the amount of fuel consumed. When driving a long distance, one should instead retain some battery energy to allow more flexibility in the control strategy. Around 48 km, the modified control strategy options cross each other, which indicates that, for a short distance, the engine should not be used to recharge the battery, while for longer distances, the engine should be operated at higher power.

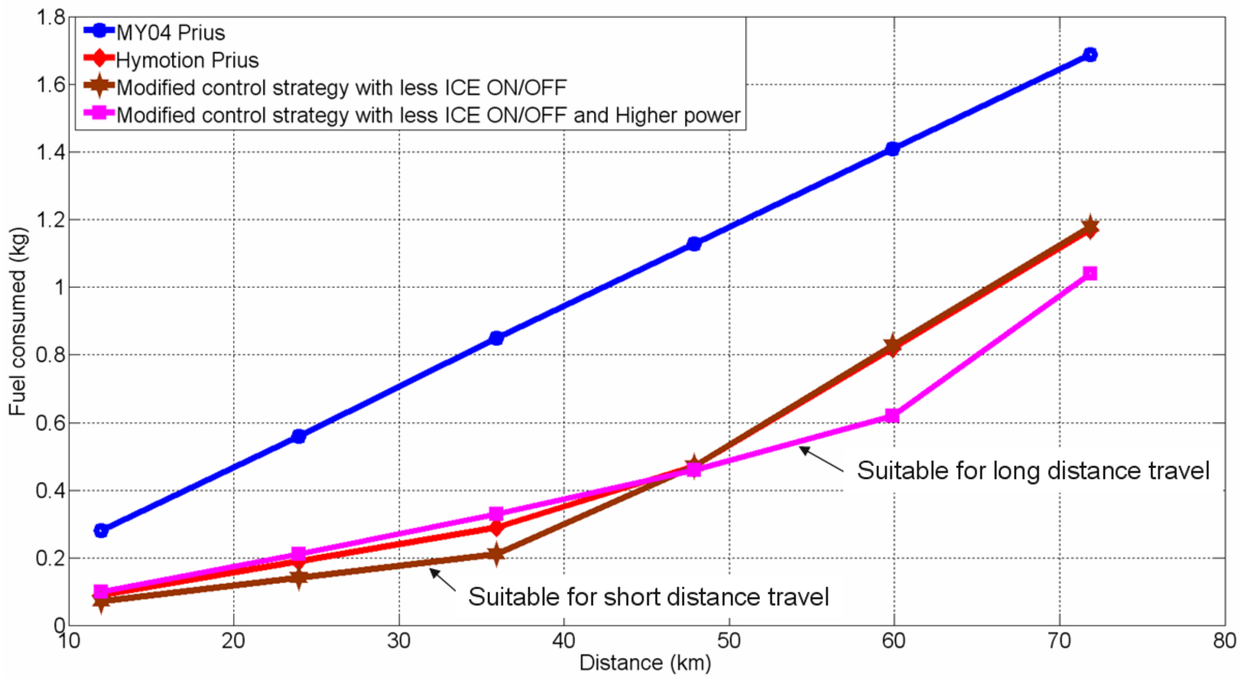

Figure 15: Fuel Consumed for Each Control Option as a Function of Distance (UDDS)

6. Conclusion

On the basis of vehicle test data collected in Argonne's four-wheel-drive dynamometer, the model of the 5-kWh Hymotion Prius was validated in PSAT. The engine ON logic and its operating points were correlated with test data.

On the basis of the analysis of the control strategy, several changes were proposed to minimize the number of engine ON/OFF events and maximize the engine's efficiency throughout the drive cycle. Each control option demonstrated its benefits for specific applications. The study demonstrated that it is preferable to operate the engine at low power during short trips and higher power during longer trips to maximize the efficiency of the entire system.

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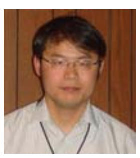

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