

Control Analysis and Thermal Model Development for Plug-In Hybrid Electric Vehicles

Namwook Kim
Argonne National Laboratory

Jongryeol Jeong
Seoul National University

Aymeric Rousseau and Henning Lohse-Busch
Argonne National Laboratory

ABSTRACT

For electrified vehicles, understanding the impact of temperature on vehicle control and performances becomes more important than before because the vehicle might consume more energy than conventional vehicles due to lack of the engine waste heat. Argonne has tested many advanced vehicles and analyzed the vehicle level control based on the test data. As part of its ongoing effort, Toyota Prius Plug-in Hybrid was tested in thermal environmental chamber, and the vehicle level control and performances are analyzed by observing the test results. The analysis results show that the control of the Plug-in Hybrid Electric Vehicle (PHEV) is similar with Prius Hybrid Electric Vehicle (HEV) when the vehicle is under a charge sustaining mode, and the vehicle tries to consume the electric energy first under a charge depleting mode. This study provides information about the operating mode and the control behaviors including the change of the control and performances under cold or hot ambient temperature. In order to validate the analysis results, a vehicle model for the PHEV is developed, and the results show that the simulation model appropriately reproduces the performances of the real world vehicle mostly within 5% even when the ambient temperature is very cold.

CITATION: Kim, N., Jeong, J., Rousseau, A., and Lohse-Busch, H., "Control Analysis and Thermal Model Development for Plug-In Hybrid Electric Vehicles," *SAE Int. J. Alt. Power*, 4(2):2015, doi:10.4271/2015-01-1157.

INTRODUCTION

Argonne has analyzed the control behaviors of advanced vehicles, such as hybrid electric vehicles (HEVs), PHEVs, and battery electric vehicles (BEVs), to develop simulation models and reproduce vehicle performances with simulation techniques [1], [2], [3]. Since many studies related to transportation technologies conducted at Argonne rely on simulation techniques [4], [5], validated models are critical. This project leverages the Argonne vehicle testing facility, which is able to test vehicles under different thermal conditions, such as -7°C or 35°C . Once analyzed, the results are used to develop individual thermal component models. One of the main reasons to develop thermal models is that the impact of temperature on vehicle performance is significant, especially for electrified vehicles. For instance, engine and battery efficiencies decrease at low temperature, or the battery is not be able to provide enough power if the battery is very cold or very hot. Further, the climate control system demands additional energy consumption under very cold weather conditions, because the engine might not provide any waste heat. In order to analyze the impact of thermal conditions, thermal component models were developed by analyzing the test data obtained from the APRF at Argonne [6]-[7]. As part of its ongoing effort to keep developing thermal models for the advanced vehicles [2], [3], the Toyota Prius

PHEV was tested in the environmental thermal chamber, and the test data were analyzed to understand the control strategies for different thermal conditions.

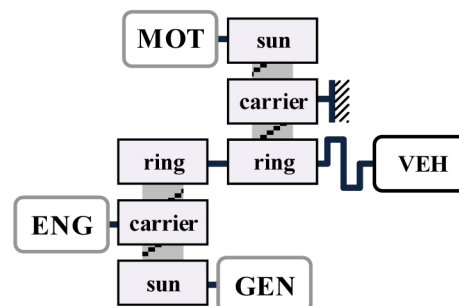


Figure 1. Configuration of Toyota Prius Plug-in Hybrid, which is the same as Prius HEV.

The Prius PHEV shares the same configuration as the Prius HEV, as shown in Figure 1. The engine and the electric machine technologies implemented in the PHEV are the same as those of the HEV.

However, the battery technology has been upgraded from a 1.3 kWh nickel-metal hydride battery to a 4.4 kWh lithium-ion battery, so that

the vehicle is able to run in EV mode on U.S. Environmental Protection Agency (EPA) driving cycles. The PHEV has a different operating mode according to the battery state-of-charge (SOC), as the vehicle is expected to drive in EV mode when it is fully charged. For instance, the vehicle tries to consume electric energy as much as possible if the SOC is higher than 28%, whereas the control behavior is very similar to the Prius with a low SOC [2].

On the other hand, there is more opportunity for the engine to be cooled down due to the longer electric driving than in the case of the HEV, or to be turned on to provide heat to a passenger compartment under the cold ambient test. In this study, the control behaviors were analyzed, and, based on the analysis results, a vehicle-level controller for the Prius PHEV was developed and integrated into the vehicle model. The comparative study shows that the simulated fuel consumptions are close to the measured ones from the tests. The data and analysis results provided in this study should be very useful to other researchers in developing thermal models in their own studies.

APPROACH

This study has four major steps. First, test data is obtained from bench dynamometer tests in environmental thermal chamber. Second, the data is imported to a vehicle simulator and is analyzed control strategies and component performances. Next, a control model and component models are developed based on the analyzed results. In the last step, the model is validated with the test data.

In detail, the vehicle was loaded on a dynamometer in APRF as shown in [Figure 2](#) in order to obtain the test data in the first step. The test is designed to make the vehicle tested on a number of driving cycles while the ambient room temperature is maintained at -7°C , 21°C , or 35°C , which is required for 5-cycle procedure defined by U.S. EPA.



Figure 2. Toyota Prius Plug-in Hybrid Electric Vehicle loaded on a dynamometer in APRF

Because the tests are appropriately scheduled to make each test have unique test condition, it is tailored to the control and performance analysis according to the test condition, especially for the thermal conditions.

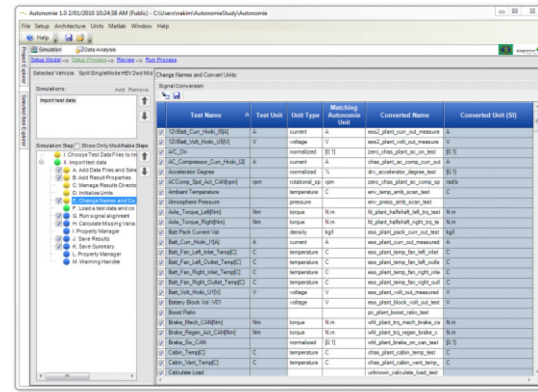


Figure 3. Importing process in Autonomie. All test data is imported into Autonomie, and signals required for the analysis are calculated in the importing process.

Argonne has provided test data on a website for public uses [8], and the data for Prius PHEV is also available and downloadable on the page. In the second step, the test data obtained from APRF is imported to Autonomie as shown in [Figure 3](#), which is a vehicle simulation tool developed by Argonne, in order to analyze the test data. During the import process, the measured signals units are converted to standard international (SI) units when needed, and additional signals are calculated for later analysis. For instance, an index parameter that represents the charge depleting (CD) mode or charge sustaining (CS) mode is generated because it is usually not measured from the test. When the data are successfully imported into Autonomie, they are analyzed to understand the control behaviors and the performance behaviors, as shown in [Figure 4](#).

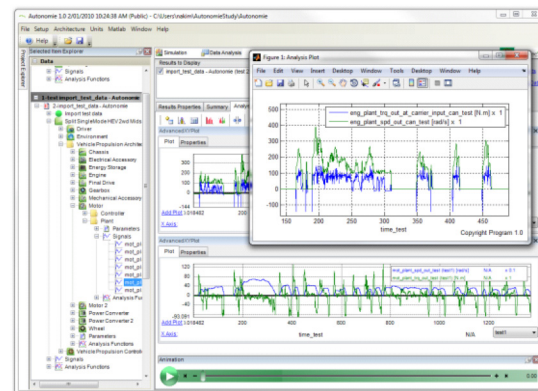


Figure 4. Analysis process. Autonomie provides functions to analyze the control behaviors from the imported test data.

The performance analysis results provide direct or useful information to estimate parameters required when component models are developed. For instance, the tire efficiencies according to the thermal condition analyzed in this step are used to obtain the coefficients of the wheel loss model. In the third step, simulation models for the controller and the components are developed in Autonomie, as shown in Figure 5, on the basis of the analyzed.

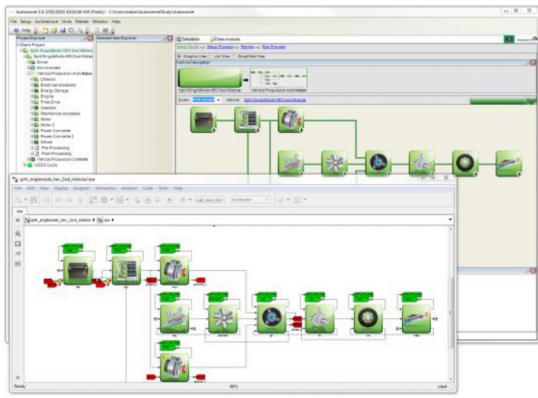


Figure 5. Running simulation model in Autonomie. The simulation results are validated with the test data obtained APRF.

In the last step, the developed model is validated with the test data. Through the validation work, the development work is completed if the vehicle model appropriately calculates vehicle performances, such as fuel economy, but also reproduces the operating behaviors of the vehicle components.

PERFORMANCE ANALYSIS FOR COMPONENTS

Argonne has collaborated with other national laboratories, vehicle manufacturers, and component suppliers to develop component thermal models [2], [3], where performances of components have been analyzed through various studies. In this study, the impact of the component temperature on their efficiency is investigated for multiple components.

Engine Efficiencies According to Engine Coolant Temperature

The engine control is affected by the engine coolant temperature. For instance, the engine should be turned on if it needs to provide waste heat to warm up the passenger compartment. The additional fuel consumed lowers the fuel economy. On the other hand, engine efficiency is also affected by engine temperature, which is not easy to characterize from the test data.

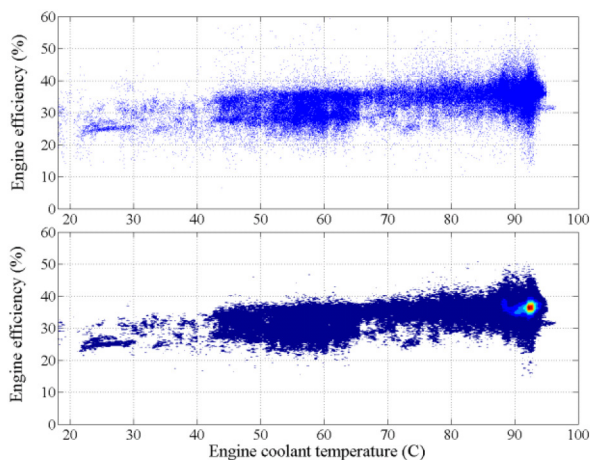


Figure 6. The change of the engine efficiency according to engine coolant temperature

Figure 6 shows the overall change of the engine efficiency according to the engine coolant temperature, where the efficiency, η_{eng} , can be calculated as:

$$\eta_{eng} = \frac{S_{eng} \cdot T_{eng}}{\dot{m}_{fc} \cdot LHV} \quad (1)$$

In Eq (1), S_{eng} and T_{eng} are the engine speed and the engine output torque, and $\dot{m}_{fc}$ and LHV are the fuel consumption rate and the lower heating value of the fuel. The engine coolant system tries to maintain the coolant temperature below 92°C, so the density of operation in Figure 6 (b) is very high at the temperature of 92°C, at which the efficiency is around 37%. However, one notices that engine efficiency continuously decreases with lower engine coolant temperature. Although Figure 6 only shows the tendency of the efficiency according to the coolant temperature, an engine map can be generated from the test data as shown in Figure 7, which is used for the engine thermal model. There are several approaches to characterizing the engine map from test data. Studies have shown that the fuel consumption rate can be calculated using a response surface methodology with input control variables as the engine speed, engine torque, and engine oil temperature [10], [11].

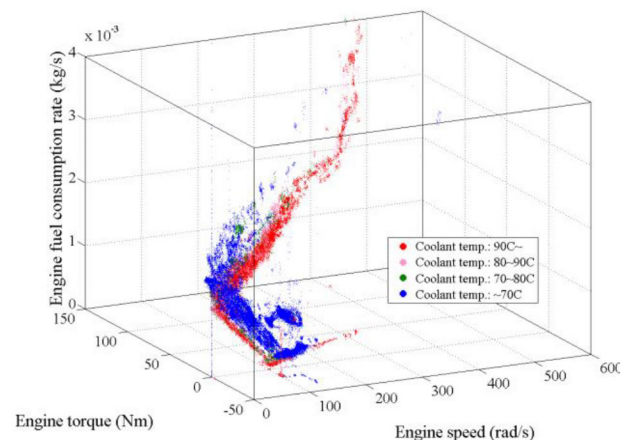


Figure 7. Engine fuel consumption rate according to the engine coolant temperature.

In our study, the fuel consumption rate under low coolant temperature is adjusted by a weighting factor calculated from test data [3]. However, an advanced idea introduced in [10], or a map obtained from tests dedicated to characterizing the engine efficiency according to engine temperature, can improve the validation results in this study.

Battery Efficiencies According to Battery Temperature

Although round-trip efficiencies can properly represent the battery efficiency, it is not easy to evaluate the battery round-trip efficiency in PHEVs because round-trip efficiency is exact only when the initial SOC is the same as the final SOC. Therefore, segments of SOC trajectories that have no difference between the initial SOC and the final SOC are selected to calculate the round-trip efficiencies, where the efficiency, η_{bat} , can be calculated as: