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Development of Validated PHEV Model through Control Analysis based on Test Data

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Executive Summary

A plug-in hybrid electric vehicle (PHEV) is a vehicle that includes both an engine and a battery system, and has a more complex control system than conventional engine vehicles. In this paper, the process of estimating and evaluating the powertrain component modeling and control system applied to the prius prime vehicle is introduced. As a result, it was possible to confirm sufficient performance by showing an error of less than 5% in fuel economy evaluation through the developed vehicle model.

Keywords: Plug-in Hybrid Electric Vehicle, Control Analysis, Model Validation, Vehicle Dynamics, Simulation Modeling

1 Introduction

In order to solve the problem of global warming caused by CO2 emissions worldwide, each country is strengthening regulations to solve this problem in various fields including the transportation field [1]. Vehicle manufacturers in each country have been keenly aware of the strengthening regulatory issues and global warming issues that are becoming a reality, and have tried to find a solution, and are developing and manufacturing electrified vehicles as a solution to the problem [2]. PHEV is a vehicle equipped with an internal combustion engine and an electrification system, and a battery driving system is possible through a charging terminal. A hybrid vehicle has a complex structure as it has an internal combustion engine and an electric system, but by utilizing the characteristics of each power source and applying an appropriate control method according to the driving situation, higher fuel efficiency can be expected compared to conventional vehicles [3-5]. Here, we would like to introduce the contents of the verification model built from the simulation vehicle modeling and control analysis process through the vehicle test conducted for Toyota's Prius Prime PHEV model.

2 Test Analysis and Model Development

In this paper, we introduce the process of constructing a simulation model based on the driving test results of the Toyota Prius Prime vehicle and increasing its reliability. The simulation model was developed based on the Autonomie software developed by Argonne National Laboratory.

Vehicle tests were conducted according to the EPA standard cycle to analyze the operating characteristics of CD (charge depleting) and CS (charge sustaining) modes, which are control strategies of PHEV. Vehicle test data was acquired through a CAN network, and additional sensors were attached to measure detailed data such as temperature, pressure, and current. Based on the acquired data, the vehicle's operating characteristics were analyzed, and control strategies were studied. Finally, by applying these analysis results to the simulation model and comparing them with actual vehicle test results, the model was validated.

2.1 Prius Prime PHEV

The Prius Prime vehicle is powered by an internal combustion engine, a battery, and two motor/ge nerator. And as shown in Fig. 1, the engine, motor and generator have a power-split structure in which the power source is transmitted by the powertrain structure to which the planetary gear is a pplied.

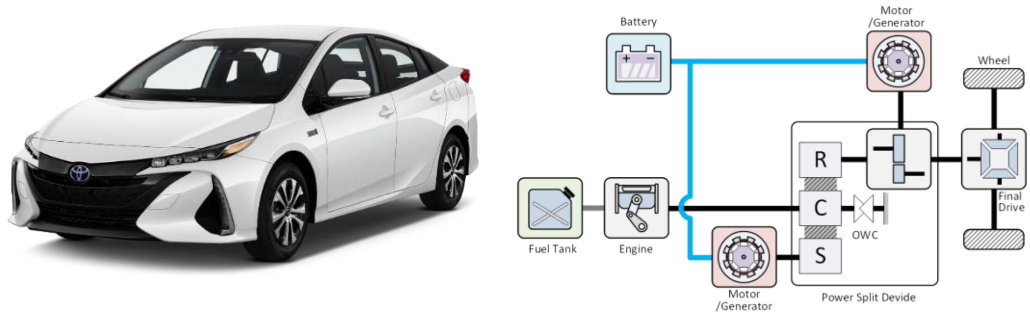

Figure1: Toyota Prius Prime Powertrain Configuration

2.2 Engine Model

In order to construct and verify the vehicle engine model, the operating characteristics of the engi ne were analyzed using the test data obtained through the vehicle test. This makes it possible to e stimate the engine BSFC map and improve the engine dynamics model.

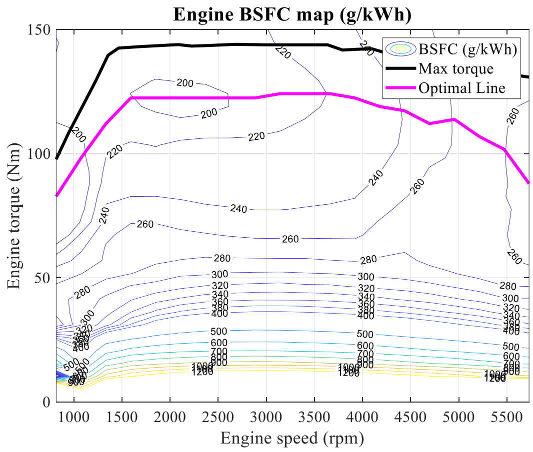

Figure2: Prius Prime PHEV Engine Characteristics

The engine characteristics of the Prius Prime PHEV were estimated based on the analyzed test dat a, as shown in Figure 1. The engine's specifications indicate that it is a 1.8L DOHC type with a maximum power of 71kW and a maximum torque of 142Nm. The estimated engine map obtained from the test analysis was applied to the simulation engine model.

2.3 Battery Model

To build a battery verification model, a generic battery model was built and the test data was anal yzed. As shown in Eq. 1, the first equivalent model of the battery was used, and in order to incr ease the accuracy of the model, as shown in Eq. 2, the characteristics of OCV and SOC represent ed by the battery SOC and operating temperature were analyzed through test data and used in the battery model [6].

$$C_p \frac{dV_p}{dt} + \frac{V_p}{R_p} = i_o \quad (1)$$

$$V_s - V_c - i_o R_o = V_o \quad (2)$$

$$V_b = V_0 + i_o R_o \quad (3)$$

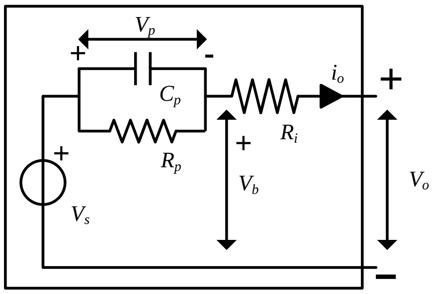

Figure3: Battery Equivalent Circuit Model

2.4 Motor Model

Models of motor operating characteristics can be built and operating efficiency maps of the prius prime main motor and generator can be analyzed from test data. The main motor of the Prius Pri me PHEV is equipped with a large motor that can produce a maximum torque of 163Nm and 53k W, which is capable of driving even in EV mode. The generator has a maximum torque of 40Nm and a power of 23kW. The characteristic maps of the motor and generator were estimated based on the quasi-static power conversion efficiency at the operating points, taking into account losses s uch as those arising from the conversion of battery electrical energy into mechanical power.

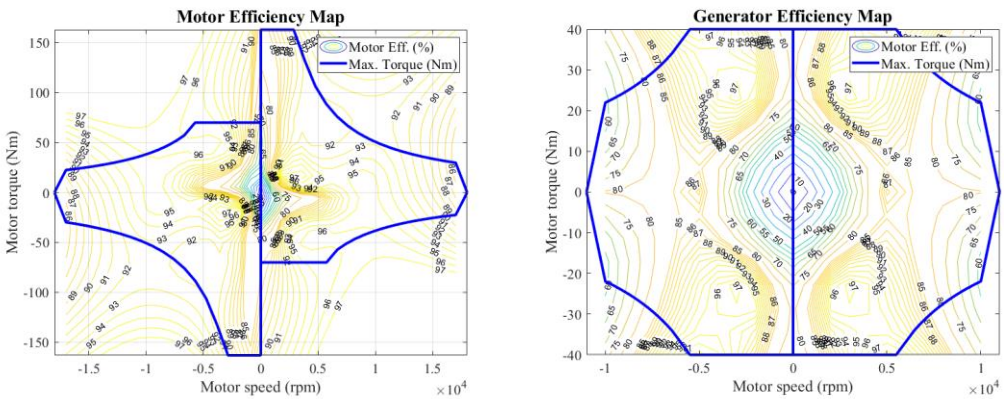

Figure4: Motor and Generator Efficiency Map

3 Control Analysis

To verify the PHEV model, it is necessary to analyze the control technique applied to the vehicle. The PHEV have CD (Charge Depleting) mode that actively consumes accumulated battery energy and CS (Charge Sustaining) mode control characteristics that maintain SOC. Control strategies such as engine on/off conditions, engine and motor power distribution control, and regenerative control were analyzed under various vehicle driving conditions, and this control strategy was applied to the model.

The first step in analyzing the control strategy of the Prius Prime PHEV was to perform CD/CS mode analysis. This is because the criteria for determining whether to turn on or off the engine, which determines whether to use EV mode or HEV mode, is applied differently depending on the mode. The biggest criterion for determining the CD/CS mode is shown to be SOC, and it was confirmed that there is a tendency to switch to CS mode when the SOC drops to about 15% or less.

After determining the CD/CS mode, we analyzed the EV and HEV mode control for determining engine on/off. In the CD mode, the vehicle's electric energy, i.e., battery, is mainly operated for driving strategy, so EV mode driving is mostly used except for special cases requiring high power. In contrast, the CS mode is a control mode for maintaining SOC, so hybrid mode occurs frequently, and engine on/off is determined by conditions such as SOC and driving power.

In EV driving mode, it is relatively easy to control the vehicle because the driving force is generated solely by the motor. However, in HEV mode, it is necessary to control the distribution of driving force between the engine and the motor, as well as the power-split transmission ratio. Compared to parallel hybrid vehicles, power-split vehicles have more flexibility, but this also means that their control can be more complex. Based on the test data, we were able to analyze the control characteristics of powertrain components by applying lever-based analysis methods of power split device to the analysis of operating points of the engine and motor. In hybrid mode, it was analyzed that the engine is controlled to operate on the optimal operating line, which is the most efficient operating range, by prioritizing the engine's operating efficiency. To achieve this, a strategy is being applied to control the engine and to control the motor and generator through the power split lever constraint equation.

We have summarized the analyzed control strategies from Figure 5 in a simplified flowchart.

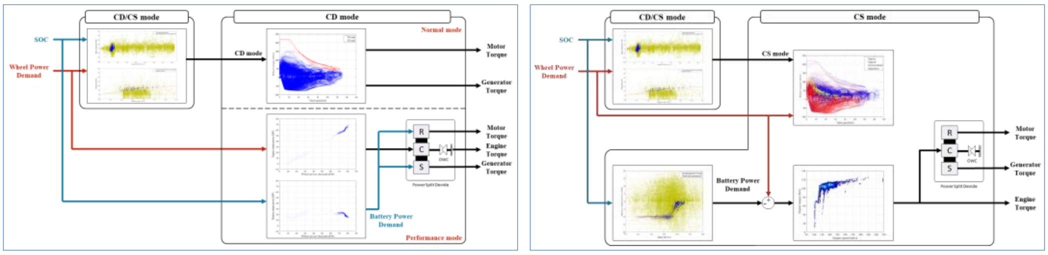

Figure5: Prius Prime PHEV Control Analysis

4 Model Validation

A autonomie software based Matlab Simulink vehicle system model was built through powertrain component modeling using test data of the Prius Prime PHEV and controller construction through vehicle system control analysis. We conducted validation of the vehicle model through simulation and compared the results with the measured results from the test data to confirm the level of reliability of the model.

Figure 6 shows the analysis results for the CD mode obtained from testing conducted on the WLTC, which is a standard certified cycle. Since it is the CD mode, the vehicle operates only in the EV mode, and the figure displays the vehicle speed, battery power, motor torque, generator torque, and battery SOC for the EV mode. The results show a high verification accuracy with an SOC relative error of 0.71%.

In addition, we conducted a simulation model verification for the CS mode in the UDDS, which is one of the standard certified cycles, as shown in Figure 7. In the CS mode, the hybrid mode operates to maintain the SOC, so we also checked the engine speed, torque, and fuel consumption. Through the verification results, we can see that the relative error in fuel efficiency between the actual test result of 33.7km/l and the simulation model result of 32.6km/l was about 3.22%, indicating that the model was sufficiently validated.

Based on the model validation results, it can be concluded that the control strategy for the Prius Prime PHEV analyzed earlier has been sufficiently implemented in the model, and the validation level has been confirmed to be sufficient as well.

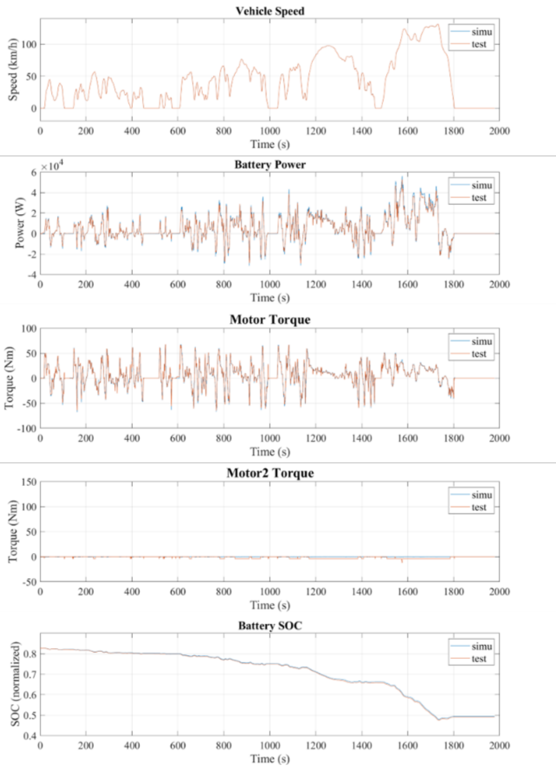

Figure6: Simulation Model Validation Result (WLTC, CD mode)

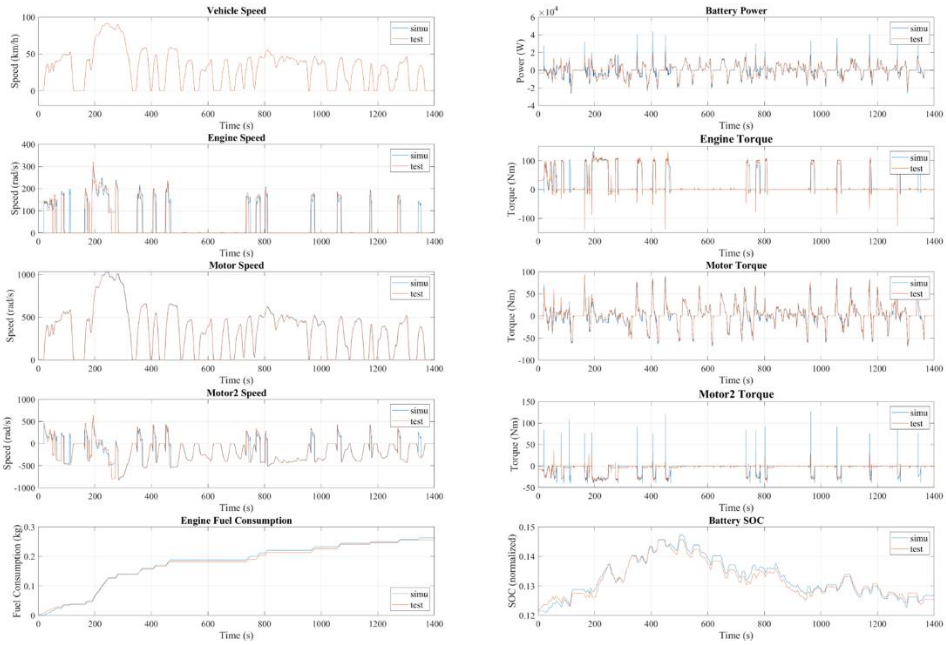

Figure7: Simulation Model Validation Result (UDDS, CS mode)

5 Conclusion

In this paper, a study was conducted to improve the verification level of the simulation model built by analyzing the component characteristics of the powertrain through vehicle driving tests. In addition, by estimating the control conditions in the driving situation and applying the control techniques that would be applied to the actual vehicle to the model through analysis by operation mode, the real vehicle verification model was established. Afterwards, based on the verification model, we plan to study the control technique applying the optimal control theory to increase the fuel efficiency.

Acknowledgments

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Presenter Biography

Tacksu Kim is a Ph.D. candidate in the Department of Mechanical Engineering, Hanyang University ERICA Campus, Ansan, South Korea. He is studying deterministic and intelligent optimal control for vehicles.