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Development of Performance Simulator for a HEV with CVT and Validation with Dynamometer Test Data

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Abstract

In this paper, control analysis was performed for a hybrid electric vehicle (HEV) equipped with a continuously variable transmission (CVT) under various driving conditions. First, a dynamic CVT model was developed by considering hydraulic and mechanical losses. The hydraulic loss accounts for the majority of the total losses at low vehicle speeds, whereas the mechanical loss accounts for the majority at high speeds. In addition, CVT ratio control and clamping force control strategies were developed, including manipulation of the CVT shift dynamics. On the basis of the dynamic model of the CVT, an HEV performance simulator was developed using Argonne National Laboratory (ANL)'s model-based simulation program, Autonomie. Second, by analysing the test results from ANL, an engine optimal operating line was constructed on the basis of the engine brake-specific fuel consumption. Third, the battery state-of-charge range and the battery characteristics of the maximum charging and discharging power were investigated. Using the analysis results, vehicle operation control strategies were developed for the acceleration, cruising, deceleration and idling modes. Also, control algorithms were developed for each vehicle operation mode. Finally, the control algorithms were verified by comparing the simulation results with the test results.

Keywords: Continuously variable transmission, hybrid electric vehicle

1 Introduction

In response to increasing regulation of fuel economy and exhaust emissions, various hybrid electric vehicle (HEV) configurations have been developed, such as the Toyota hybrid system, the Transmission Mounted Electric Device system of the Hyundai-Kia motor company, and the Integrated Motor Assist (IMA) system of Honda.

Unlike the other HEV systems, the Honda IMA system uses a parallel hybrid configuration, in which the motor is directly connected to the engine [1]. The motor power is transmitted to the wheel through a continuously variable transmission (CVT). To improve the HEV system efficiency, the efficiencies of the components, such as the engine and motor, have been studied [2] Also, a cylinder idling system was investigated to decrease the friction resistance of the engine during regenerative braking [3]. However, these studies have been performed mainly at the component level. To improve the HEV efficiency, a control strategy for each driving mode needs to be designed for the target HEV configuration.

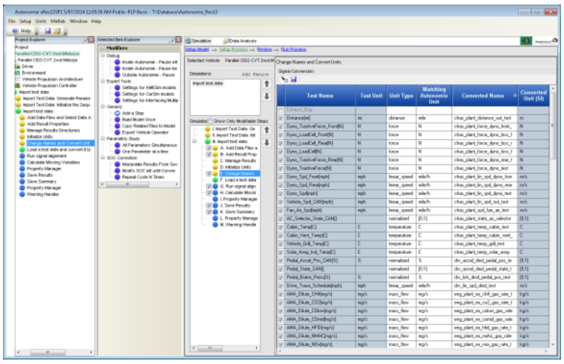
In the present study, a vehicle performance simulator for the Honda IMA system was developed, and the driving mode control strategy was analyzed using the experimental results from dynamometer tests. The vehicle performance simulator and vehicle driving mode control strategy developed in this study were validated by comparing the simulation results with the experimental results.

2 Test Description

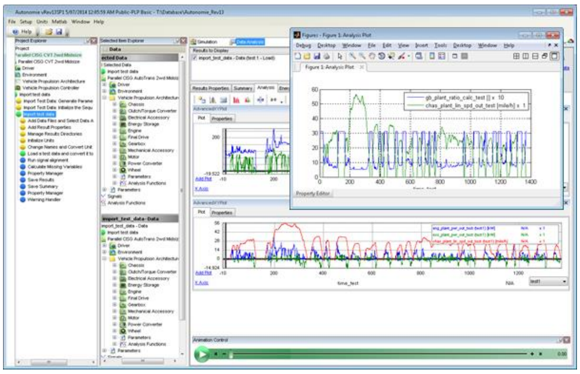
The Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory (ANL) is designed for researchers who conduct vehicle benchmarking and testing activities, and a number of studies have been published [4-6]. Engineers use the facility to run vehicle tests on a two- or four-wheel-drive dynamometer to measure numerous metrics, including performance, energy consumption, and emission output. To set an achievable goal for vehicle modeling, one needs to first quantify uncertainties related to test measurements. ANL has been conducting very extensive testing of advanced vehicles, in terms of both instrumentation and number of tests.

Because of the large amount of data, a generic process is necessary to automatically generate reports that will allow engineers to quickly analyze data quality [7]. This process is based on three steps: First, the data are imported to a vehicle simulator and analyzed for control strategies and component performance. Second, control models and component models are developed on the basis of the analysis results. In the last step, the model is validated with the test data.

ANL has provided test data on a website for public use [8], and the data for the Honda IMA system are available and downloadable from the Web page. In the first step, shown in Figure 1 (a), the test data obtained from the APRF are imported to Autonomie, which is a vehicle simulation tool developed by ANL, for analysis. During the import process, the parameters are calculated from measured/recorded signals to evaluate their accuracy with respect to each vehicle component. Mathematical equations can be used to calculate the effort and flow at the input/output of each component. These parameters can then be used to calculate the power, energy, and efficiency. For example, the final-drive rotational input and output speeds, which are usually not measured in the dynamometer tests, can be calculated from the wheel speed. When the data are successfully imported into Autonomie, they are analyzed to understand the control behaviors and the performance behaviors, as shown in Figure 1 (b).



(a) Importing process



(b) Analysis process

Figure 1: Importing and Analysis process in Autonomie

The performance analysis results provide direct or useful information for estimating the parameters required when component models and control models are developed. For instance, the battery power according to the wheel power and the battery state of charge (SOC) analyzed in this step is used to obtain the energy management strategy. In the last step, the developed model is validated with the test data, as discussed in detail in the following sections.

3 Development of Performance Simulator

3.1 Vehicle configuration

Figure 2 shows the configuration of the target HEV system. This system has a parallel hybrid configuration, which consists of the engine, motor, CVT, and final reduction gear. The driving motor is connected to the engine, and the CVT is installed between the motor and wheel. Since the engine is mechanically connected to the motor, the engine has the same speed as the motor. The engine and motor speed can be controlled independently of the vehicle speed, owing to the CVT's continuously variable feature.

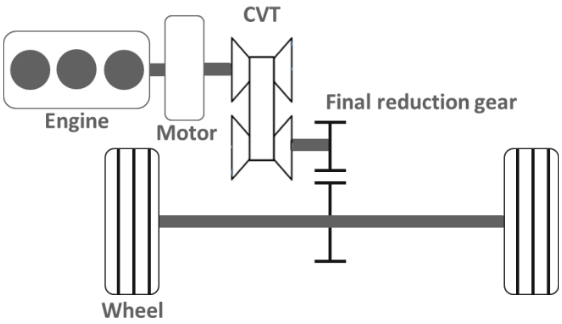


Figure 2: Vehicle configuration of Honda IMA system with CVT

3.2 Component modeling based on the experimental results

Dynamic models of the engine and motor were obtained using the characteristic maps obtained from the ANL experimental results (Figures 3 and 4) and were represented as first-order systems. Component models, such as battery, clutch, and vehicle models, were constructed on the basis of the Autonomie models and were scaled by considering the specifications of the target HEV System (Table 1).

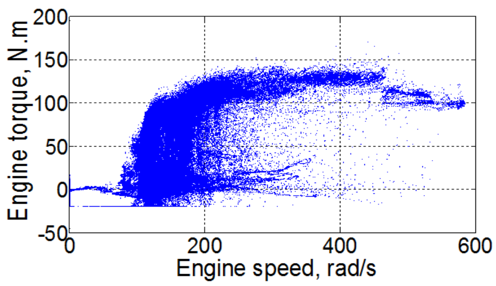


Figure 3: Engine characteristic map for target vehicle

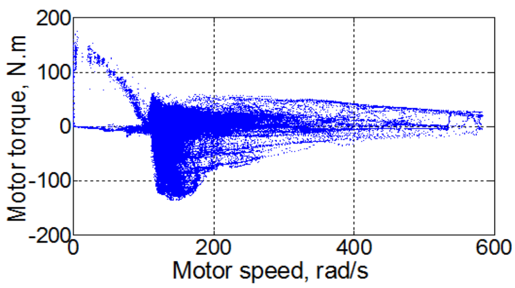


Figure 4: Motor characteristic map for target vehicle

Table 1: Specifications of target vehicle

Engine	Displacement	1500 cc
	Torque	172 Nm @ 5500 rpm
	Power	82 kW @ 5500 rpm
Motor	Max. power/torque	17 kW/106 Nm
	Max. speed	9500 rpm
Battery	Number of cells	40
	Nominal cell voltage	3.6 V
	Rated pack energy	0.675 kWh
TM	CVT ratio	3.172–0.529:1
	Final drive ratio	3.94:1
Vehicle	Weight	1295 kg
	Tire radius	0.381 m

3.3 CVT system

The CVT has a direct influence on the efficiency and performance of the vehicle. Therefore, in the CVT model, shift dynamics, a variator control algorithm, and system losses should be included to evaluate the fuel economy and vehicle performance. The CVT shift dynamics were represented as follows [9,10]:

$$\frac{di}{dt} = \beta(i) \cdot \omega_p \cdot (P_p - P_p^*) \tag{1}$$

where i is the CVT gear ratio, ω_p is the primary pulley rotational speed, P_p is the applied primary pressure, P_p^* is the primary pressure at a steady state, and $\beta(i)$ is the experimental constant, which varies with the CVT gear ratio.

The CVT line pressure provides the clamping force to transmit the torque. If the line pressure is too high, it causes hydraulic pump losses. On the other hand, if the line pressure is too low, CVT belt slip occurs. Therefore, it is important to maintain the proper line pressure. In this study, the line pressure (secondary pressure) was determined from Fujii's formula [11]. Then, the primary pressure was obtained from the FpFs map that is the thrust ratio of primary clamping force to secondary clamping force and is constructed in the experiment [12].

The CVT system loss consists of the hydraulic loss and the mechanical loss. The hydraulic loss comes from the pump loss to provide the CVT clamping force when the pump generates the line pressure. The mechanical loss is caused by the torque loss from the slip between pulley and belt. The hydraulic loss has a dominant influence on the total CVT system efficiency when the vehicle is driving at low speed, whereas the mechanical loss is the main part of the CVT system loss at high speed. The CVT system model was developed by considering the hydraulic and mechanical losses, using the experiment-based map data [13–16]. Figure 5 shows the hydraulic pump loss and the mechanical loss in the CVT model.

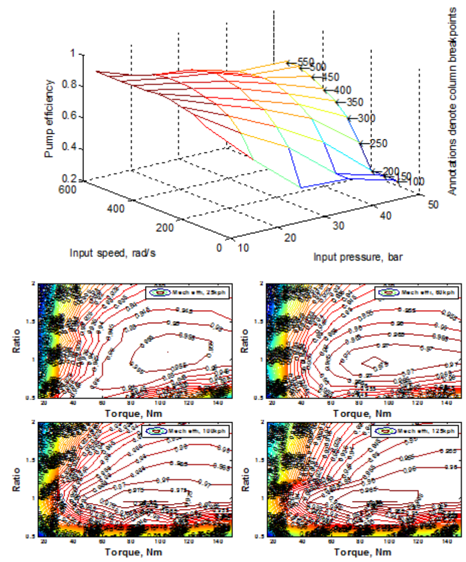


Figure 5: Hydraulic pump loss map (top) and mechanical loss map (bottom) in the CVT model [13–16]

A CVT system model is shown in Figure 6. Demanded secondary pressure (P_{s_des}), demanded primary pressure (P_{p_des}), and primary pressure at a steady state (P_p^*) are calculated from the CVT control block. The out torque (T_{out}) is obtained through the CVT plant block by considering the CVT loss.

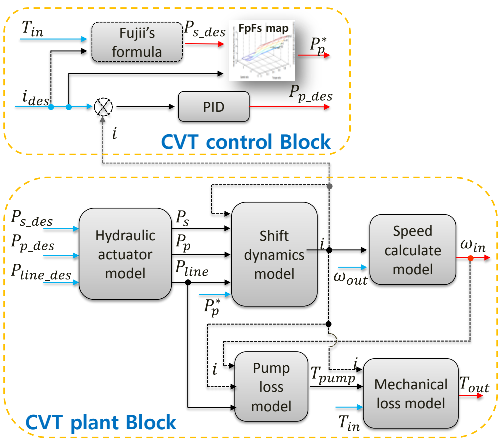


Figure 6: CVT system model

3.4 Vehicle performance simulator

The component and models developed in this study are integrated into Autonomie as shown in Figure 7. The high-level controller determines the vehicle driving mode, and the low-level controller performs the variator control and CVT gear ratio control.

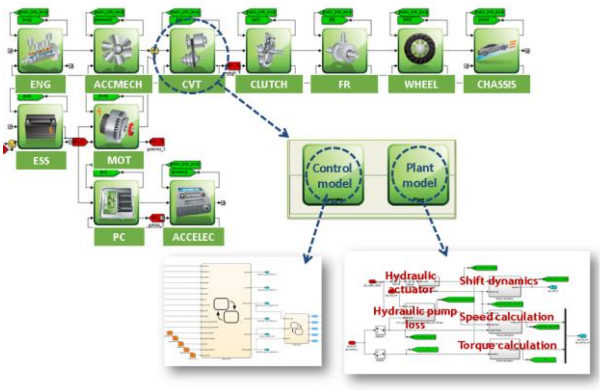


Figure 7: Vehicle performance simulator for a HEV with CVT

4 HEV Driving Mode Control Strategy

In the target HEV, the engine is a main power source and the motor assists the engine according to the vehicle operating conditions and the intention of the driver. Three driving modes were used [17]: EV mode, Engine mode, and HEV mode (see Table 2).

Table 2: Vehicle operating modes of target vehicle

Mode	Operating Conditions
EV mode	Low-speed cruise/low power
Engine mode	Slow acceleration/high-speed cruise
HEV mode	Start-up/aggressive acceleration

When the vehicle is driving at low speed or the demanded power is low, the vehicle is operated only by the motor in EV mode. During high-speed operation, start-up, or aggressive acceleration, the vehicle is operated by the engine in Engine mode or HEV mode.

4.1 Engine optimal operating line

Figure 8 shows the experimental results for the demanded engine power vs. engine speed. It is seen that the engine was operated in the optimal operating region, which has the highest engine thermal efficiency. The engine optimal operating line (OOL) was derived from the experimental results. In region A, it is noted that the engine performed above the OOL. This is because the engine cannot be operated on the OOL at high vehicle speed and low engine power, owing to the limited CVT ratio.

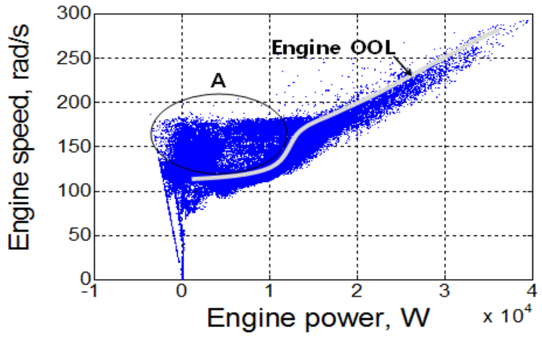


Figure 8: Engine optimal operating line

4.2 EV mode

The driving mode control strategy was determined by the engine on/off state. When the vehicle drives at low speed, the system is operated only by the motor, without engine operation. Figure 9 shows the experimental results for the demanded wheel power and actual motor power. Region B indicates the operation points where the vehicle is operated in EV mode. It is found that the motor takes all of the demanded power when the wheel power is lower than 4 kW. However, if the wheel power is larger than 4 kW, the motor and engine operate together and the motor assists the engine (region C).

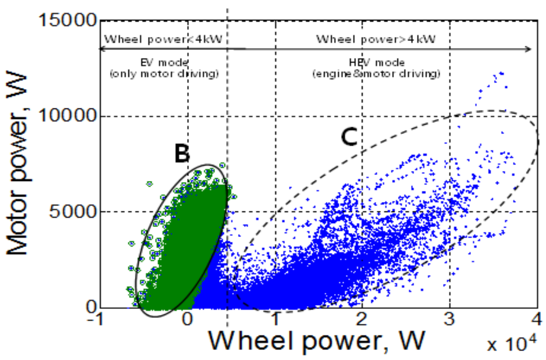


Figure 9: Experimental results for motor power vs. wheel power

Figure 10 shows the experimental results for the battery SOC vs. motor power. As shown in this figure, the use of the battery was restricted at a SOC below 0.4. If the battery SOC decreases below 0.4, the battery should be charged using the engine power; when the battery SOC is higher than 0.8, the battery should be discharged by the motor to prevent overcharging.

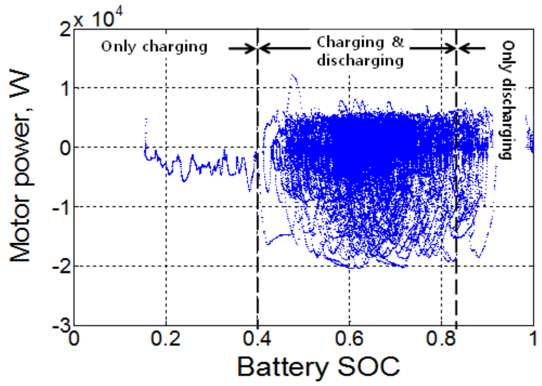


Figure 10: Experimental results for motor power vs. battery SOC

4.3 HEV mode and Engine mode

In HEV and Engine mode, the engine was operated to manage the demanded power at high speed or acceleration. In these modes, the engine is controlled to operate on the OOL for high engine thermal efficiency. However, since the range of the CVT gear ratio was limited, the motor worked to exert additional control of the engine operating points.

In Figure 11, the experimental results for the motor, engine, and CVT input torque vs. the engine speed are shown. The CVT input torque was measured at the input shaft of the transmission. The OOL_high and OOL_low curves were determined from the experimental results by considering the engine operation for each vehicle driving mode. In determining the OOLs, the transient operation trajectory during mode changes was neglected. When the CVT input torque is larger than OOL_high, the vehicle cannot be operated by the engine alone because engine operation above the OOL_high curve causes decreased engine thermal efficiency. Thus, the vehicle drives in HEV mode (motor assist) and the motor assists the engine (Figure 11B). On the other hand, when the vehicle needs less torque than OOL_low, the vehicle drives in HEV mode (motor generating); the motor works as a generator and the extra engine power is stored in the battery (Figure 11C). As shown in Figure 11, the vehicle driving mode was determined by considering the demanded CVT input torque and the engine OOL operation.

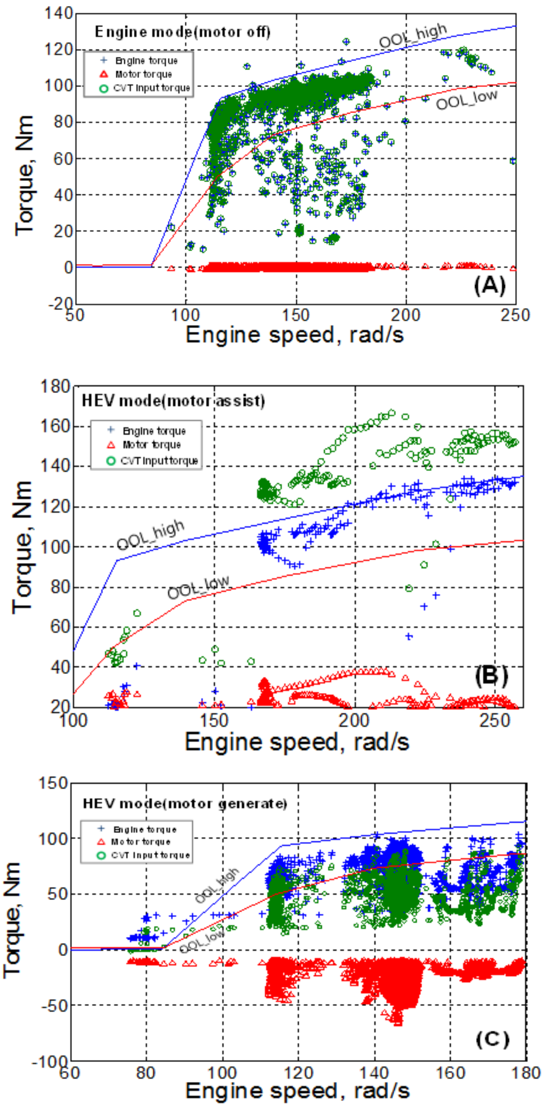


Figure 11: Vehicle operating points in HEV modes and Engine mode

5 Validation Results

The vehicle performance simulator and driving mode control strategy developed in this study were validated by comparing the simulation results with the experimental results from ANL. Figures 12 and 13 show the validation results for the target HEV system on the UDDS (city driving) and HWFET (highway driving) cycles. The CVT shift dynamic model was validated by comparing the CVT gear ratios: the simulation result for the CVT gear ratio agreed well with the experimental result. The battery was charged or discharged according to the driving mode control strategy. In EV mode or HEV mode (motor assist), the battery SOC decreases. In HEV mode (motor generating), the battery SOC increases. In Engine mode, the battery SOC is sustained. The simulated vehicle speed, gear ratio, engine torque and battery SOC were in close accordance with the experimental results, demonstrating the validity of the simulation model and control strategy.

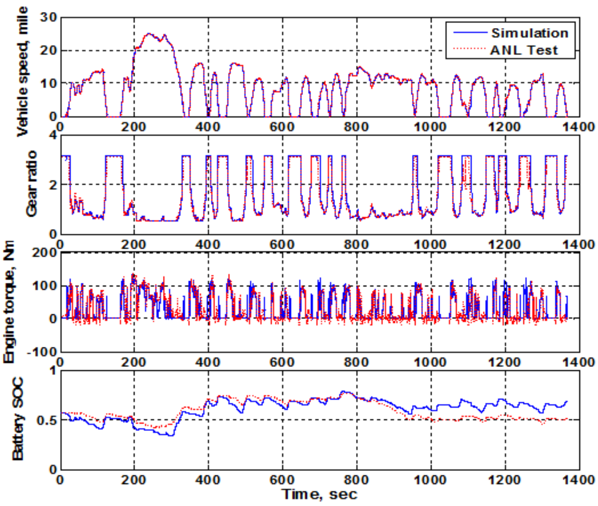


Figure 12: Validation results for UDDS cycle

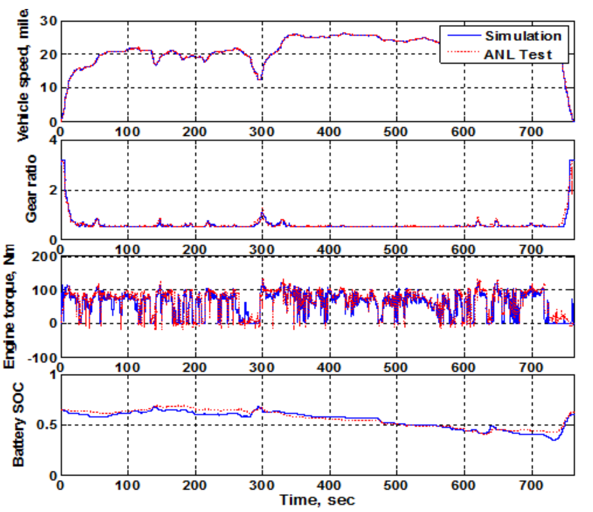


Figure 13: Validation results for HWFET cycle

The normalized cross correlation power (NCCP) value, which shows the correlation level, was used to compare the simulation and experimental results quantitatively [18]. The NCCP value was calculated as follows:

$$NCCP = \frac{\max[R_{xy}(\tau)]}{\max[R_{xx}(\tau), R_{yy}(\tau)]} \quad (2)$$

$$R_{xy}(\tau) = \lim_{\tau \to \infty} \frac{1}{T} \int_0^{\tau} x(t) \cdot y(t-\tau) dt \quad (3)$$

Table 3 shows the correlation level of the simulation and experimental results for the HWFET and UDDS cycles. It was found that all NCCP values exceed 0.9, showing a high level of correlation.

Table 3: NCCP values for UDDS and HWFET cycles

Cycle	Vehicle Speed	Gear Ratio	Engine Torque	Battery SOC
HWFET	0.99	0.98	0.90	0.97
UDDS	0.99	0.93	0.90	0.96

6 Conclusions

The vehicle driving mode control strategy was investigated for a parallel HEV equipped with a CVT. To develop the driving mode control strategy, a performance simulator was developed. The CVT system model was constructed considering the shift dynamics, the variator control algorithm, and hydraulic and mechanical losses. From the experiment results, the engine OOL was derived and the vehicle driving mode control strategy was analyzed using the dynamometer test results. From the test results on the mode control parameters, such as demanded wheel power, battery SOC, and engine operating points, the vehicle driving mode control strategy was developed. The performance simulator and driving mode control strategy were validated by comparing the simulation results with the experimental results. NCCP values for the vehicle speed, CVT gear ratio, engine torque and battery SOC exceeded 0.9, demonstrating the validity of the simulation and control strategy. The performance simulator and control strategy are expected to be used in the design of a HEV equipped with CVT.

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