Vehicle-level control analysis of 2010 Toyota Prius based on test data

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Abstract

The Prius, a power-split hybrid electric vehicle developed by Toyota, has been the top-selling vehicle in the United States hybrid electric vehicle market for the last decade. The transmission system of the vehicle is a frequent theme of study for hybrid electric vehicles. However, the control concept of the vehicle is not well known, since analyzing control behaviors requires well-designed facilities to obtain testing results and well-defined processes to analyze the obtained results. Argonne National Laboratory has these resources and capabilities. In addition, Argonne has produced a reliable simulation tool, Autonomie, by which a vehicle model for the 2010 Prius is developed on the basis of the analyzed results, and it is validated with the results of testing. The developed model demonstrates that results of vehicle performance from simulation are close to those of from real-world tests—within 5%. The main focus of this study is to provide information about the supervisory control for the 2010 Prius, so that researchers can reproduce the real-world behavior of the vehicle through simulations. The analyzed control ideas based on the testing results will be very helpful in terms of understanding the control behavior of the vehicle, and the information resulting from this study is useful to develop the controller for the vehicle at a simulation level.

Keywords

Supervisory control, vehicle testing, simulation and modeling, Prius, hybrid electric vehicles, Autonomie

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Introduction

The Toyota Prius is the first hybrid electric vehicle (HEV) to be manufactured on a large scale. Since its worldwide launch a decade ago, this HEV has dominated the HEV market share due to its outstanding fuel economy and future-oriented design. In 2009, Toyota debuted the latest version of the vehicle model, the 2010 Prius. The latest version features a reduction gear added between the traction motor and the power-split device. The fuel economy is improved for highway driving because the reduction gear possibly reduces the power-converting loss during high-speed driving. Information about the change of configuration or the change of components, such as the reduction gear, the engine size, or the motor size, has been released by the company.[1–3] This type of information is otherwise obtained by conducting a tear-down study.[4,5] The control strategy of the vehicle, however, is not well published because it is considered confidential company information. Although it could be studied through reverse engineering, sufficient data obtained from well-designed tests are required to analyze the control strategy. Whereas several studies have applied advanced control strategies on the power-split system,[6–9] many of them have suggested the improvement of performance on the strategies compared with performance obtained by a rule-based control. The basis control in those studies should reproduce the behavior of the real vehicle, so the improvement has real meaning. In this study, we tried to determine the control strategy of the 2010 Prius by analyzing a number of test runs, which were conducted in the Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory. The approach described in this paper focuses on the vehicle-level control strategy, so high-level control algorithms, such as the engine-on/off control, power-splitting strategy, energy management, and component target control, are analyzed from the test data. Based on the analyzed results, a rule-based controller is designed by Matlab Simulink, and it is deployed in

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Autonomie—a forward-looking simulation tool developed by Argonne. Finally, the simulation results obtained from Autonomie are compared with the test results to validate the developed vehicle model. The objective of this study is to reproduce the vehicle's behavior through simulation. Accomplishing this objective requires well-designed facilities for testing the vehicle, well-defined processes for analyzing the test data, and reliable simulation tool for validating the developed vehicle model. Fortunately, by satisfying these three necessary conditions, Argonne could reproduce the vehicle's behavior through simulation. Since this study provides essential information about the real-world control strategy, we believe that it will be quite helpful to researchers who study advanced control strategies for HEVs.

Vehicle test

The APRF was designed to conduct vehicle benchmarking and testing activities, in which vehicle performances such as fuel economy, energy consumption, emissions output, and acceleration are revealed by highly accurate measurements. The tested vehicle, the 2010 Prius, and the testing process is briefly introduced in this section.

Prius MY10

A significant change in the model year 2010 Toyota Prius (MY10) compared with the previous version, the model year 2004 Prius (MY04), is that a reduction gear is added between the ring gear and the motor output, as shown in Figure 1. The final drive ratio is reduced from 4.1 to 3.3. The reduced gear ratio allows the output of the power-split device, or the ring gear, to have a lower speed than the speed of the previous version, so the operating speeds of the components are different from the operating speed of Prius MY04. For instance, assuming that the desired engine speed of MY10 is, simply, the same as the speed of MY04, then the absolute speed of the generator for MY10 could be lower than the speed of MY04 at high-speed driving, as shown in Figure 2. In this situation, the system is able to reduce the converting power flow between the electrical path and mechanical path because the reduced speed of the generator converts less power from the mechanical part to the electrical part than when the generator is at high speed. Therefore, the system efficiency is increased by reducing the loss as the converting power flow is reduced. Although the desired engine speed of MY10 is different from the case of MY04 because the engine power is changed from 57 kW to 73 kW, the reduction of the output speed really saves the energy by reducing the converting loss at high-speed driving.[10] On the other hand, the motor power of MY10 is increased compared with the motor of MY04, from 50 kW to 60 kW, and the net propulsion power is increased from 80 kW to 100 kW, as shown in Table 1. Also, the fuel economy is increased, and a detail comparison analysis based on testing data shows that the system efficiency of MY10 is improved compared with MY04.[10,11]

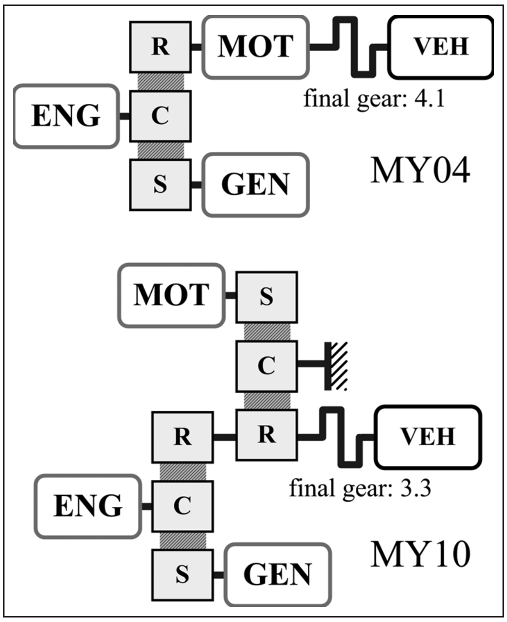

Figure 1. Configurations of Prius MY04 and MY10. (S, C, and R in the figure denote the sun gear, carrier gear, and ring gear of the planetary gear systems.)

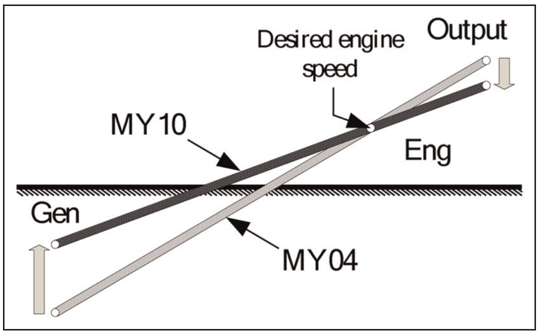

Figure 2. Schematic of the operation speed of the power-split device based on lever systems. (The generator in the Prius MY10 could have a lower absolute speed than the speed of the Prius MY04 in this condition.)

Table 1. Simple comparison between Prius MY10 and Prius MY04. (Fuel economies indicated on the sticker are increased for both city and highway driving for 2010 Toyota Prius.)

	MY04	MY10
Engine power	57 kW	73 kW
Motor power	50 kW	60 kW
Net power	80 kW	100 kW
Fuel economy: sticker (city/highway, combined)	48/45, 46 mile/gal	51/48, 50 mile/gal
Fuel economy: estimated by drivers[11]	47.5 mile/gal	49.2 mile/gal

Test bench

Argonne has systematic processes to conduct vehicle tests, and the testing procedures are classified by two levels. At the Level 1 test, the test signals that are easy to access are obtained from the test bench, by which we could test the overall performances of the vehicle, such as fuel economy, acceleration, and emissions. At the Level 2 test, additional sensors are designed and deployed into the real vehicle to obtain the detail performances. For instance, the torque and speed sensor are mounted between the engine output axis and the transmission input axis, or thermometers are attached to each point of components on the oil circulation loop. Further, the control unit's input and output ports are analyzed to obtain the signals used in the unit at the Level 2 test. The test for Prius MY10 is conducted at both Level 1 and Level 2. The test results from Level 2 are used in this study. The vehicle is tested on 25 various driving schedules on the dynamometer according to a standard procedure of APRF (Figure 3), which includes different speed and grade conditions for steady speed runs, as well as various certificated driving schedules, such as the Urban Dynamometer Driving Schedule (UDDS), the Highway Fuel Economy Test (HWFET), LA92, and US06. Further, the engine is started at both high temperature and low temperature to figure the effect of the engine temperature on the driving performance. For the analysis of the control strategy, the steady speed testing results are primary used to analyze basic control patterns and to establish control rules. Test results obtained from the various driving schedules are used to verify the established rules.

Filtering the test data

Figure 4 shows a general organization of controllers. Although noise signals are already filtered by sophisticated data-acquisition processes at the test bench, the obtained test data are not supposed to be directly used for the control analysis, since the obtained data are frequently output signals of a control unit or system feedbacks, as shown in Figure 4. The desired information to analyze control algorithm is, however, the control target signals produced at the target generating process because additional control signals are added in the target tracking process according to current states. For instance, the obtained signals might show that the engine speed is accelerating from 2500 r/min to 3000 r/min, while the control target is 3000 r/min. Because it is not easy to extract only the control target from the test signals, only the results that are instantaneously steady are obtained from filtering processes, which are utilized to analyze the control target.

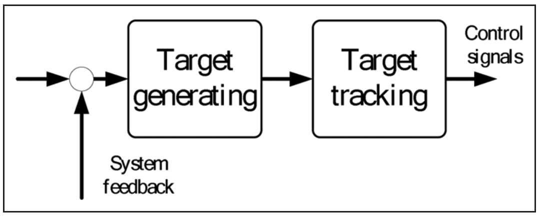

Figure 4. Typical organization of the controller.

The instantaneously steady signals are defined by the engine speed and the engine torque in our study. If the engine speed rapidly increases or decreases, the motor and the generator are assumed to produce additional torque to track the desired engine speed. Based on the test data, we assumed that the signal is supposed to be close to the control target, or the tracking torque demands possibly vanish, when the engine acceleration or deceleration does not exceed 5 rad/s^2 for 1 s. Although alternative criterion was possible to extract the steady signal, the filtering parameters were very effective in leaving enough test data to analyze the results. Besides this filtering process, several other processes are applied to obtain the analysis-ready data. For instance, the test signals when the engine temperature is lower than 85 °C were ignored when analyzing the engine control target, or the test data were categorized by the driving mode, such as hybrid electric driving mode, pure electric driving mode, and neutral driving mode. Further, we established optional processes to filter the test data according to various conditions, such as engine operating mode, requested torque level, pedal status, and direction of the battery power flow. These predefined filtering processes are utilized to effectively analyze the control algorithm of Prius MY10, and the detail applications are introduced in following sections.

Figure 3. Prius MY10 tested in the Advanced Powertrain Research Facility.

Vehicle-level control

An energy management strategy is a very essential concept for the vehicle-level control of HEVs, which is realized by controlling the power-split ratio between the engine power and the battery power. The other control variables could be determined based on the optimal operating of the system if the power-split ratio is given by the strategy. The results from 25 driving tests on the dynamometer are carefully analyzed, and the control strategy is described by three primary control concepts, such as the engine-on/off control, state-of-charge (SOC) balancing, and engine operating target control.

Engine-on/off control

To avoid inefficient operation of the engine, the vehicle is controlled to run in a pure electric vehicle mode when the requested power is low, if the SOC is not significantly low. However, considering that the battery capacity is 6.5 Ah, and the nominal output voltage is just above 200 V, we could reason that the SOC would be rapidly depleted in the pure electric vehicle mode—even for a few minutes. Therefore, the pure electric vehicle mode is limited, and the engine should be turned on in the appropriate time. Finally, understanding the pattern of control for the engine is essential for understanding the mode control of the vehicle. By analyzing the test data, several engine operating states and control flows are defined, as shown in Figure 5.

Although the real control strategy could be more complicated than the depiction in the figure, the analysis based on the control flows in Figure 5 well describes the behavior of the engine. The testing results from all 25 runs are used to analyze each control direction. Table 2 shows the status of the engine speed and the fueling at each state. The detail analysis for the signal flows could be explained according to operating conditions.

Engine-on condition. The control flows when the engine is turned on are 1→2 and 1→3. First of all, the flow, 1→2, is active if the requested power demand calculated from the driver's pedal signal exceeds a threshold that is a function of SOC, as shown in Figure 6. Each point in the figure indicates the requested power demands at the wheel when the engine is turned on. The threshold for the engine-on condition is a function of SOC, so that the engine is turned on early if the SOC is too low. Additionally, the engine is also turned on earlier than the expected demand power level if the requested torque is high, which occurs on tests at several harsh driving cycles. This control allows the engine to support the system to satisfy the requested performance. Another control flow, 1→3, is active when the engine temperature is very low. In this situation, the engine is forced to be turned on, and it is not turned off until the engine temperature is high enough, which also will be discussed in this study.

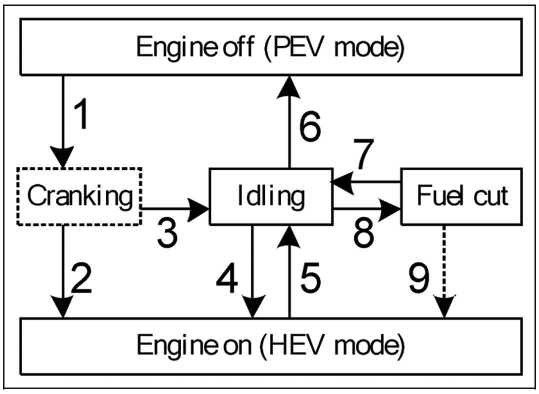

Figure 5. State machines for the engine operation.

Table 2. Descriptions for the engine status.

	Engine speed	Fueling
Engine off	0	Off
Cranking	Accelerating	Ready to fuel
Idling	Idle speed	Idling
Fuel cut	Idle speed	Off
Engine on	Controlled	Controlled

Engine-off condition. A main control flow for the engine turned off is 5→6 or 5→8, as shown in Figure 5. Unfortunately, it is not easy to catch out the power threshold for the engine-off condition because the requested power is rapidly reduced when the drivers, sometimes suddenly, take their foot off the pedal, whereas they used to smoothly push the pedal in acceleration. Our testing does not catch up the exact power demand for the engine-off condition. However, we can state that the engine is always turned off when the drivers take their foot off the pedal, and there is a hysteresis for power demand between the engine-on condition and the engine-off condition. The overall threshold power level for the engine-off condition depicted in Figure 7 is relatively lower than the power for the engine-on condition shown in Figure 6. On the other hand, the condition that determines the direction between the two alternatives, 5→6 and 5→8, is the vehicle speed, as shown in Figure 7. Whereas the control flow 5→6 shows that the engine is fully turned off, the system maintains the engine speed on idle without

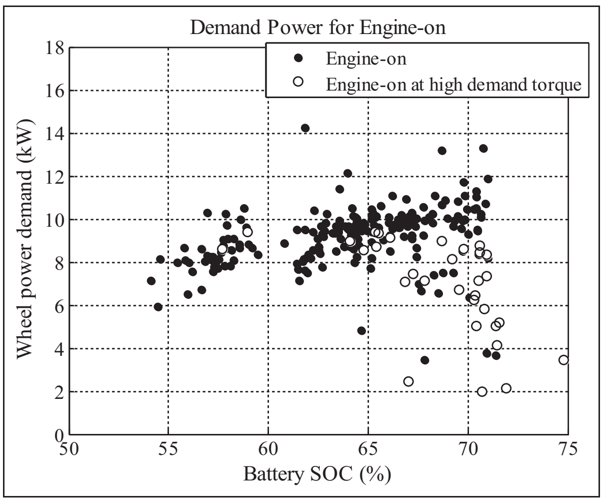

Figure 6. Threshold for turning the engine on.[10] (The engine is turned on if the requested torque is high, even though the requested power is far below the power threshold line.)

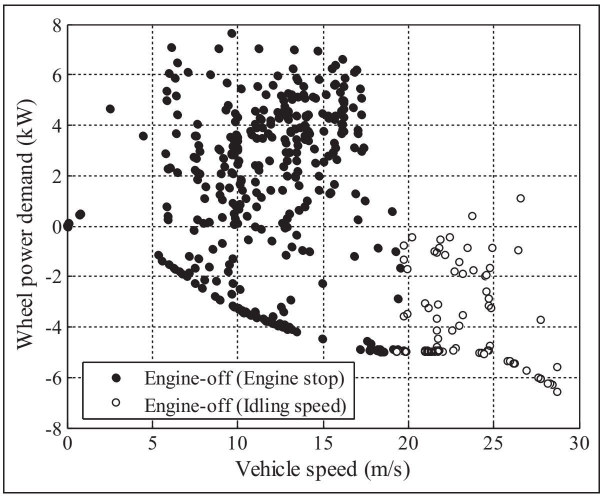

Figure 7. Two different situations for the engine-off condition. (If the vehicle speed is higher than a threshold, the engine stays on the idle speed.)

fueling by providing torque from the generator to the power-split device when the vehicle speed is over about 20 m/s. Although the system consumes additional energy because of the friction torque for the engine, this control helps the engine become ready to be turned on rapidly on highway driving.

Other conditions. The two conditions for the engine on and engine off are the main control concepts that determine the driving mode, such as PEV or HEV. Besides these conditions, several other conditions influence the behavior of the engine. For instance, the engine is turned off from the fuel cut state through the control flow, 7→6, when the vehicle speed is reduced below 20 m/s at the fuel cut state. In the test results, a direct path from fuel cut to engine-off is not really preferred. Instead, the system tends to go into the idling state for under 1 s before the engine is fully turned off. On the other hand, the control flow 4 is active when the engine temperature is very low. Further, the engine stays on the idling state, whereas it is turned off with the control flow, 5→6, when the temperature is not high enough. The control flow 9 is an unconfirmed transition in our tests because it is confused with the control flow, 7→4. If the requested power is above the threshold, the engine is turned on, but it is not clear in our testing results whether it goes through the idling state or goes directly to the engine-on state. Although these conditions are less important than the conditions for the engine-on and engine-off, they are necessary to reproduce the vehicle's behavior in simulations, and we define all the control flows to realize the control in a forward-looking simulator.

SOC balancing

One of main issues about the control of HEVs is to manage the energy balance. The SOC of the battery is supposed to be controlled in an appropriate range. In general, the utilized range of the battery is limited to a small part of all usable ranges, since it is known that aggressive usage could harm the life cycle of the battery.[12,13] Research about the battery characteristics is not part of our study, but considering the real-world concept for SOC balancing is very useful and enables us to understand the behavior of the battery operation. The SOC trajectories on steady speed tests with different grades are analyzed to figure out the control concept for the energy balance. A driving schedule, as shown in Figure 8, is used for the steady speed tests, but a different grade is applied to each test. Only the SOC trajectories on the HEV mode are considered to analyze the control concept for the SOC balancing. Figure 9 indicates that the SOC is controlled to be restored to the reference value, such as 60%. The tendency means that the energy management strategy is designed to ensure that the SOC is controlled in a

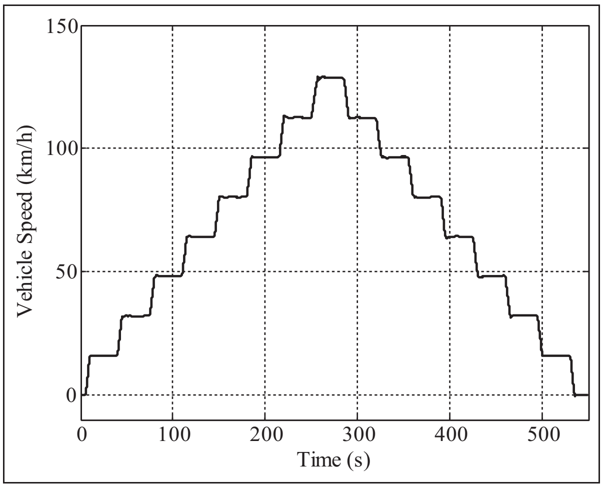

Figure 8. Steady speed tests. (The tests are done at different grades, such as 0%, 0.5%, 1%, 2%, and 4%.)

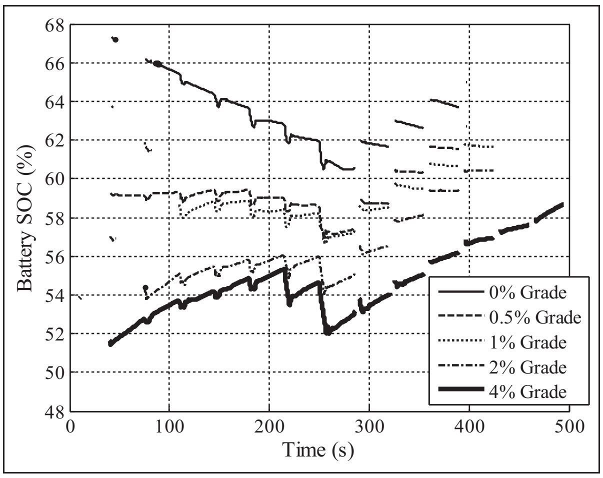

Figure 9. Restituted patterns of SOC in steady speed tests.

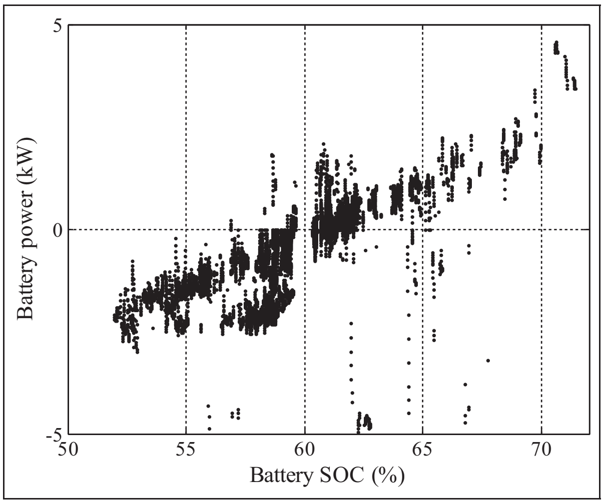

Figure 10. Battery power of the test according to SOC.[10]

reliable range, rather than to use a wide range of the SOC to improve the system efficiency. As stated earlier, the steady targets are extracted from the test data from all 25 test runs. We can conclude that the desired battery power is determined by the SOC, which enables the SOC to return to 60% when the engine is turned on, as shown in Figure 10. Although all 25 test results do not show a completely identical pattern, the control based on proportional gain can be considered as a primary approach for the SOC balancing. When it comes to the energy management strategy, we can conclude that Prius MY10 has two main control strategies to balance the level of the SOC. First, the engine is turned on early if the SOC is low. Second, if the engine is turned on, the battery power is controlled to recuperate the electrical energy if the SOC is low. These two concepts enable the system to avoid the depletion of electrical energy. Further, the control concept depicted in Figure 10 indicates that the engine produces less power than the requested power, so the SOC could be restored to an appropriate level if it is too high.

Engine operation

The mode control strategy and the energy management strategy for Prius MY10 are described in the previous two sections. However, the control targets for each component cannot be calculated until the engine operating targets—engine speed and torque—are determined, because the power-split transmission possibly has a number of alternative control targets, even though the desired battery power is determined. Just as only the operating points of the battery in steady state are used to generate the control target for the SOC balancing, only the operating points of the engine in steady state are selected and used to generate the engine control targets. Additionally, we remove the engine operating points from the selected points if the engine temperature is below 80 °C, because the engine is controlled by a different rule to warm up the engine when the temperature is low, which will be discussed in the following section. While additional torque appears in the test results because of transient behaviors, the extracted control targets are positioned in a narrow range, as shown in Figure 11. This approach is applied to all 25 testing results, and the operation points are obtained, as shown in Figure 12. It seems that the engine is controlled to track a predefined operating line. In conclusion, if the desired battery power is determined by the rule shown in Figure 10, then the desired engine power can be determined based on the requested power and the desired battery power-the power loss according to component efficiencies could be considered to obtain the accurate desired power of the engine. Considering the engine operation targets in Figure 12, we could generate the desired engine speed and torque based on the desired engine power. Finally,

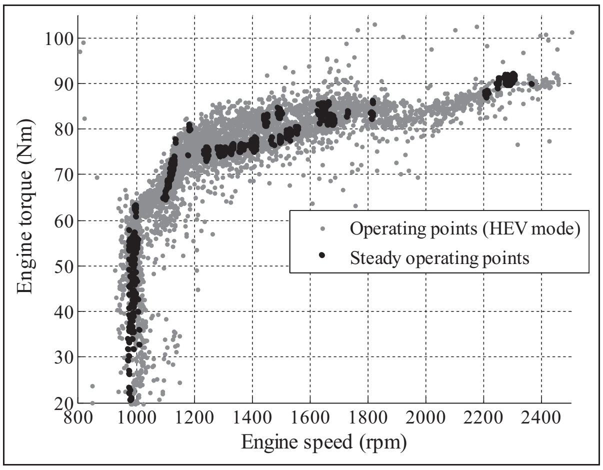

Figure 11. Engine operating points. (The steady operating points are used to analyze the control target.)

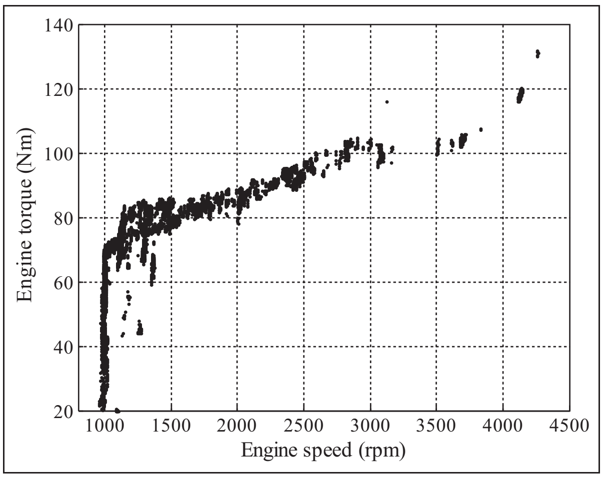

Figure 12. Engine operating points for only the instantaneous steady state.

other control signals for the motor and generator can be calculated based on the given information.[14] All these control decisions can be realized by applying the three concepts described in this paper, such as engine on/off, SOC balancing, and the engine's operating target. Besides these concepts, sophisticated control ideas for drivability or safety should be applied to the real vehicle. However, the control concept described by the three ideas provides important information for understanding the energy management control of the real-world Prius.

Other control concepts for the Prius MY10

Although the three control concepts described in the previous sections are highly related to the vehicle performance, there are other interesting control concepts that explain the vehicle's behavior. In this section, we will introduce several control ideas or informative results, which are intended to be useful to realize the control model in simulations.

Regenerative braking. The energy recuperated from the braking energy is very important to enhance the system efficiency for HEVs, but the control idea of the regenerative braking is generally simple, such as recuperating as much energy as possible, as shown in Figure 13. In the figure, a mechanical braking system is installed in the vehicle, but it is not supposed to operate if the motor could recuperate all the braking energy. The mechanical brake is utilized only when the electrical braking torque is not enough, or if the vehicle speed is low, as shown in Figure 14. The figure shows the operating points of the motor when the motor produces retarding torque for the braking. It also indicates that the maximum braking torque is constrained by the maximum battery power, 28 kW,[5] rather than being limited by the motor power, 60 kW. It is quite natural that the electrical braking is not preferred at low speed, since the electrical system not only is inefficient at low speed but also is less stable than the mechanical braking system at that speed.

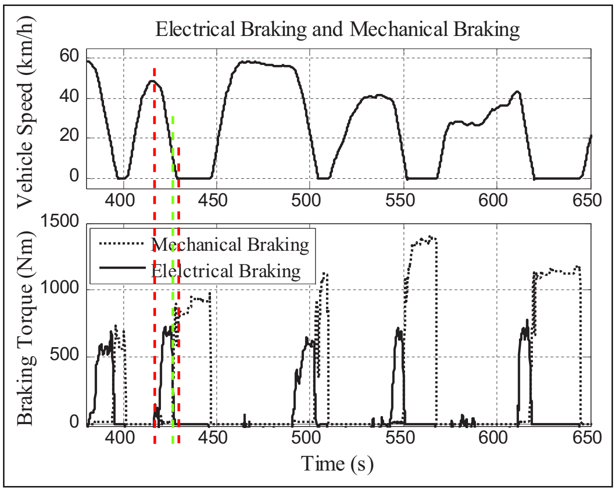

Figure 13. Braking torque at the wheel.

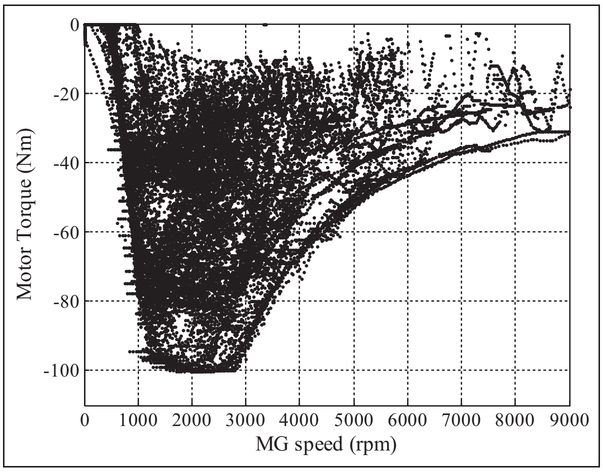

Figure 14. Operating points of the traction motor on the braking mode.

Control according to engine temperature. The thermal management system for the engine is designed to heat it up as soon as possible,[1] but it is impossible to completely avoid operating the engine in low temperature. Figure 15 shows the temperatures of the coolant output of the engines obtained from three different tests, which were conducted on the same driving schedule, UDDS, but started at different initial engine temperatures, such as 22.5 °C, 69 °C and 88.5 °C. As shown in the figure, if the vehicle starts at a cold temperature, the engine is turned on as soon as the driver turns on the vehicle, even though there is no pedal input from the driver. Further, the engine speed does not go down below a

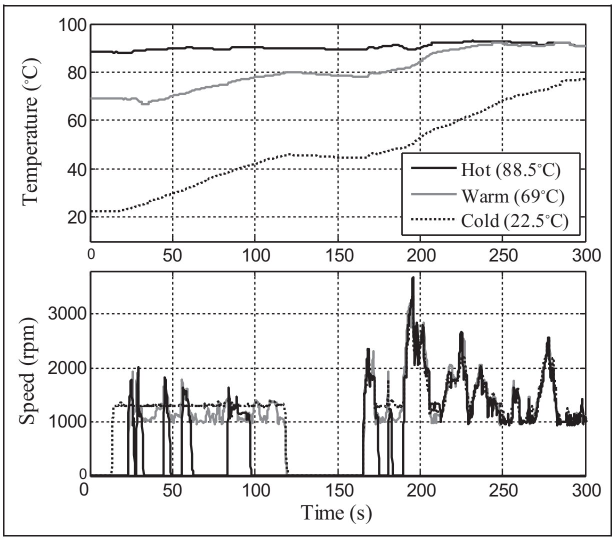

Figure 15. Three different engine operations according to the engine temperature.

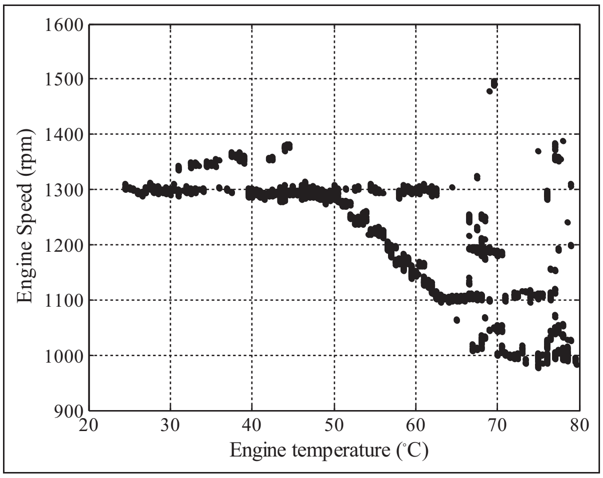

Figure 16. Operating speed of the engine when the engine temperature is low (< 80 °C). (The adequately hot temperature seems to be about 85 °C in the tests, so the condition is used to clearly exclude non-idle operating points.)

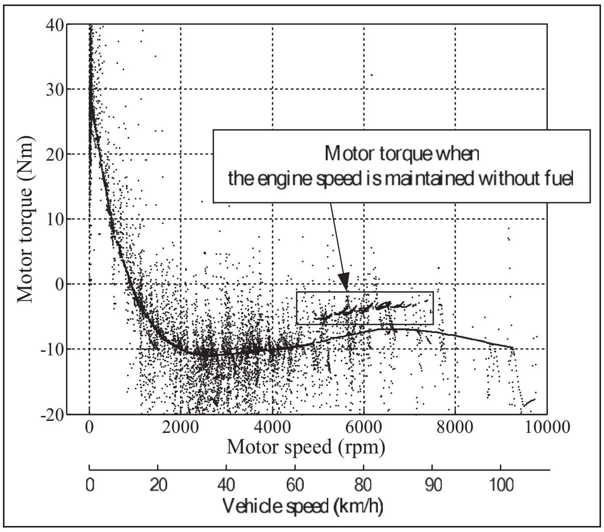

Figure 17. Motor operating points when there is no pedal input.

certain speed, which is a little higher than the idle speed. In this situation, the engine does not provide any power to the vehicle until the coolant temperature reaches 35 °C, which means that the engine operates under 35 °C only to heat itself up, even though the control rule described above demands that the engine provides power for propulsion. On the other hand, in the case of a warm start, the engine is turned on according to the condition of "engine-on", as explained earlier. The engine is, however, not fully turned off until the temperature is high enough, about 85 °C. Instead, the operating speed of the engine is controlled according to the temperature. Figure 16 shows the idling speed obtained from 17 runs when the engine temperature is below 80 °C. The figure indicates that the engine speed is controlled in a high speed level if the temperature is lower than 50 °C, and it is controlled according to the temperature when the temperature is between 50 °C and 65 °C. It is known that the coolant system of the engine does not fully operate when the engine temperature is low.[1] With this concept, the engine speed control enables the engine to be warmed up rapidly, so that the engine is able to operate in efficient conditions as soon as possible. Under the warm condition (below 85 °C), the engine provides the required torque and tracks the engine target speed described earlier if the engine is supposed to be turned on according to the condition introduced above. In the last case, a hot start, the engine simply follows the rule described earlier, so the engine is fully turned off if the requested power is below the engine-off threshold or zero.

Motor control at zero pedal signal. One of the interesting concepts for the vehicle is that the system is controlled to imitate the behavior of conventional vehicles when there is no pedal input. For instance, without the pedal input, the motor produces positive or negative torque to provide a corresponding behavior of the automatic transmission. From the test results, the motor operating points obtained when the driver does not provide any pedal signal are shown in Figure 17. As indicated in the figure, the motor produces retarding torque when the vehicle speed is over 16 km/h, and it produces propulsion torque under that speed. This control could make drivers feel as though they are driving an automatic transmission vehicle by providing the same behavior as an automatic transmission vehicle—the torque converter in the automatic transmission produces multiplied driving torque or retarding torque according to the speed ratio between an impeller and turbine. On the other hand, the motor produces a retarding torque less than normal when the engine is on the fuel cut state, since the power-split device by the engine and the generator also provides retarding torque, so the motor needs to compensate the torque. Although this control idea is not highly related to the vehicle performance, an effort has been made to enable drivers to experience the same drivability as with a conventional vehicle.

Requested torque based on a pedal signal. In general, the requested torque is possibly calculated based on a pedal signal and maximum torque at a simulation level. To understand the behavior on a real-world basis, we analyzed the real requested torque for Prius MY10 based on the testing results. The requested torque signal is measured at the control unit, and it is founded that the torque is determined by the vehicle speed and the pedal positions, as shown in Figure 18. The requested torque curves are obtained according to the pedal position, but the curves for 80% and 90% are not obtained because there are not enough points to generate the curves, whereas we could generate the curve for 100% from the

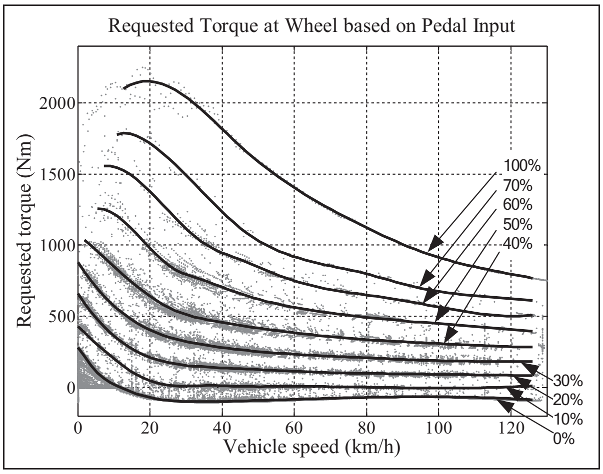

Figure 18. Requested torque used in the control unit.

Table 3. Parameters used for the vehicle model of Prius MY10.

Parameter	Values used in simulations
Vehicle mass	1531 kg (curb. 1380 kg)
Engine	1.8 l, 73 kW(@5200 r/min), 142 Nm (@4000 r/min)
Motor	PMSM, 60 kW, 207 Nm
Generator	PMSM, 42 kW
Battery	Ni-MH, 27 kW, 201.6 V (6.5 Ah)
DC-DC converter	Boosted up to 650 V
Gear ratio of the planetary gear set 1	78/30
Gear ratio of the planetary gear set 2	58/22
Gear ratio of final drive	55/54 * 77/24
Wheel radius	0.305 m

accelerating test. The maximum requested power on the full pedal curve is slightly less than 90 kW near 120 km/h, and the power requested is increased as the speed is increased, so the net power of Prius MY10, 100 kW, seems to be realized above 120 km/h. In this section, we have introduced several control ideas of the Prius based on test results. Although these ideas are not closely related to parameters associated with the vehicle's performance, we tried to apply the control ideas to the simulation, and this information would be helpful to realize the vehicle performance as close as possible to the real-world vehicle.

Model validation with Autonomie

Figuring out the control strategy, we can evaluate the performance of the vehicle at a simulation level. The simulation technique not only saves the effort to evaluate the performance, but also makes it easy to apply new technologies to the system without too much cost. For that approach, reliable simulation models that are validated from test results are crucially important.[15,16] On the basis of the analysis in the previous sections, we developed a vehicle model for Prius MY10, as shown in Figure 19, and Table 3 shows the parameters used in the vehicle models. Autonomie, a forward-looking simulator developed by Argonne National Laboratory, is used to validate the developed model. The detail simulation techniques and the simulation results are introduced in this section.

Supervisory controller

While pre-built component models in Autonomie are loaded and used for building up the vehicle model, the supervisory control model is newly designed to realize the control concepts described earlier. To realize the concept, two processes, target generating and target tracking, are organized in the controller, as shown in

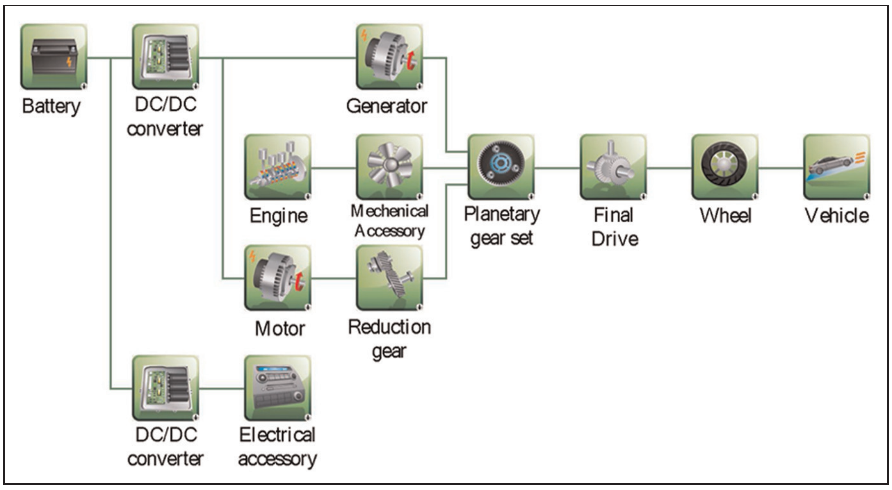

Figure 19. A schematic of the powertrain configuration used in simulations. The system also includes DC/DC converters, a mechanical accessory, and an electrical accessory. In reality, the reduction gear is realized by a planetary gear set. The motor can be used as a generator, and vice versa.

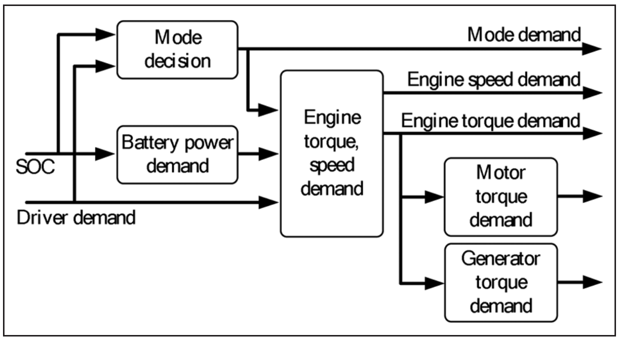

Figure 20. Primary signal flows in the supervisory controller.

Figure 4. The analyzed results in this paper are applied to the target generating process, and the control signal flows of the process are detailed in Figure 20. In the flows, the mode decision block determines the status of the engine according to the rules described above. The battery demand block generates the desired battery power on the basis of the current SOC (as explained earlier), so the engine demand block could calculate the desired speed and torque demand on the basis of the desired engine power (also discussed earlier). If the engine desired torque is calculated, the motor torque and the generator torque are calculated to make the system operate in equilibrium. Although the figure shows simple flows of the control signals, supporting control concepts should be considered for the supervisory control. For instance, the constraints for each component must be complementary considered to calculate the practical constraint for the control signal because, for example, the maximum torque or speed of the generator possibly limits the maximum torque of the engine in the power-split device. Further, the generator should be controlled to crank the engine when the engine is turned on, or it should produce torque when the engine speed is sustained at idle speed without fuel supply. The necessary supporting control concepts are designed and integrated in the target generating process. On the other hand, the target tracking process receives the control targets from the target generating process and calculates the additional torque to chase the desired engine speed. The target tracking control could be analyzed based on transient behavior, but it is not included in this study. Instead, a general idea to track the control target based on a time constant is used in the developed controller,[10] whereas an optimized control concept could be applied to the power-split device control.[9]

Simulation results

The developed control model is deployed in Autonomie, and four representative cycles, two normal cycles and two harsh cycles, are selected to validate the control model, as described in Table 4. Figure 21 depicts the comparison between the simulation results and the testing results on US06, in which the engine operation obtained from the simulation is very close to the testing results. Especially, the results show that the engine-on/off control, based on the condition described in the section on engine-on/off control, appropriately follows the real behavior of the engine in the test. The simulation results reproduce the trajectory of SOC and the trajectory of cumulative fuel consumption as well, as shown in Figure 22, which means that the energy

Table 4. Descriptions for the selected cycles.

Cycle name	Driving type	Harshness
UDDS	Urban	Normal
LA92	Urban	Harsh
HWFET	Highway	Normal
US06	Highway	Harsh

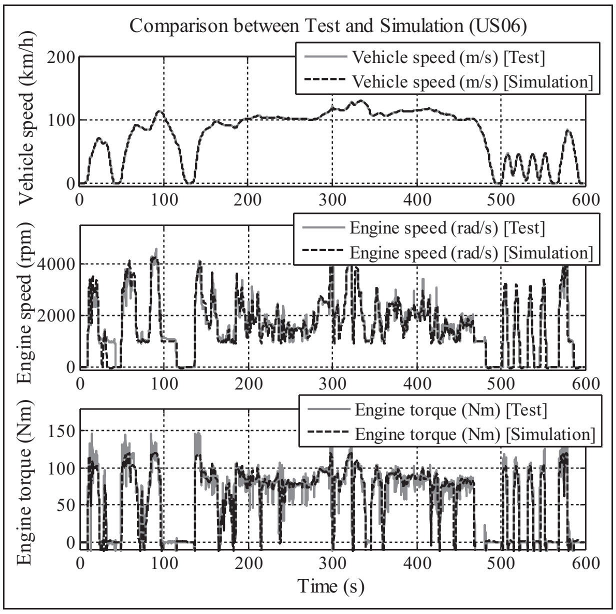

Figure 21. Simulation results and testing results on US06.

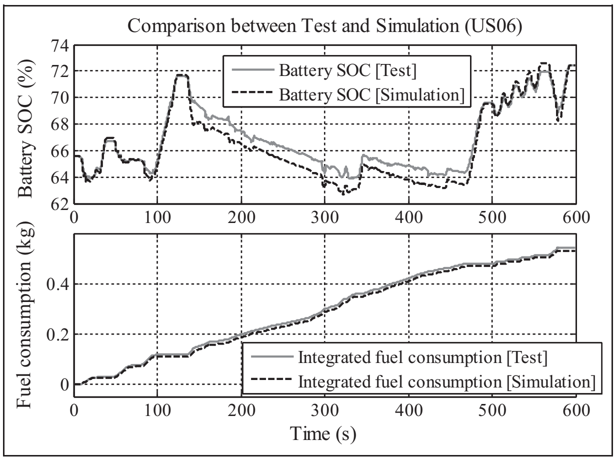

Figure 22. SOC and fuel consumption trajectories of the simulation.

Table 5. Comparison of the performances of the simulation results and the testing results.

Cycle name	Fuel consumption (g)		Final SOC (%)	
	Test	Simulation	Test	Simulation
UDDS	303.6	293.4 (–3.36%)	56.31	54.42 (–3.36%)
LA92	530.0	522.5 (–1.42%)	69.52	71.37 (+ 2.66%)
HWFET	423.5	441.0 (+ 4.13%)	65.27	65.60 (+ 0.51%)
US06	544.6	535.4 (–1.69%)	72.42	73.84 (+ 1.92%)

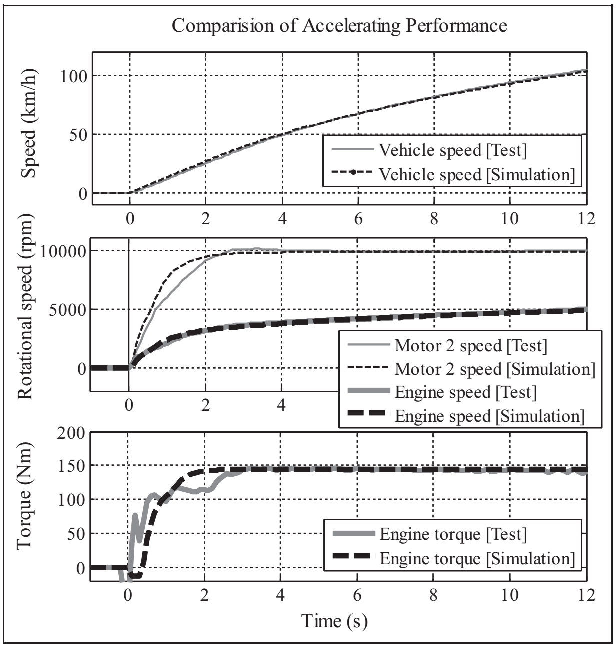

Figure 23. Accelerating performance from the simulation.

management strategy based on the analysis is well designed to follow the real performance of the vehicle. The comparison of the simulation results and the testing results is conducted for the four certificated driving schedules. The results are listed in Table 5.

All the results listed in the table indicate that the vehicle performances obtained by the simulation are close to the real vehicle's results, within 5%. In that the engine map is generated from only the driving tests, the performance of the simulation can be improved if accurate component maps are obtained. On the other hand, the accelerating performance of the simulation model also is compared with the testing results. The accelerating performance from 0 to 100 km/h in the simulation is 11.274 s, whereas it was 11.005 s in the test, which takes 2.44% more than the testing results. Although the difference in the performance is not huge, the engine operating target for the full accelerating performance looks a little bit different in the simulation, which means that Prius MY10 possibly uses a modified control target for the engine when the driver requires full performance from the system. The accuracy for the accelerating performance simulation could be also improved if a detail engine map is provided to analyze the engine maximum torque characteristic.

In general, when evaluating the performance of conventional vehicles that have a single power source (like an engine), we are able to estimate performance values that are very close to the real values if the simulators have high-fidelity models because the control strategy for the single power source is simple enough to reproduce in the simulations. It is, however, not easy to implement the control strategy for HEVs in simulations, because a redundant degree of freedom exists in the control for HEVs-the control for HEVs instantaneously has many possible solutions according to the power split ratio among hybrid power sources. In other words, the gear shifting control of the conventional vehicle could be instantaneously optimized at the request of the driver, but the power split ratio between the engine and the motor in HEVs is only optimized on the basis of the full information of the driving schedule. Thus, without precise information on future driving, there is no absolute control solution for HEVs that maximizes fuel economy. Because having precise future information about driving is not realistic, the controllers designed for real-world HEVs should include heuristic rules originating from the developer's experiences and insights. Although the rules are possibly based on technical analysis, tests are needed to confirm that, indeed, the rules have a technical basis. Therefore, understanding the rules applied to the controller by observing testing results is not only a very important step, but also the only effective way to develop vehicle models for real-world HEVs.

Conclusion

As stated in the introduction, the main objective of this study is to provide useful information for researchers by reproducing the behavior of Prius MY10 and evaluating the performance of the vehicle at a simulation level as close as the real-world test. For that purpose, we tried to describe the main control idea of the vehicle, which can be used in realizing the control concept. We hope that the analyzed results and the figures provided in this study are helpful to other researchers. The evaluation in simulations requires a reliable simulator, and the simulation model should be validated by comparing the simulation results with the real test results. This means that the entire work requires well-designed testing facilities, appropriate analyzing processes, and a good platform for the simulation. In this study, the processes to develop the vehicle simulation and validate the model are introduced. The simulation results indicate that we can reproduce the vehicle behavior for HEVs, by which we can evaluate the vehicle performance within 5% at simulation. We believe that interesting research will be possible based on this study. For instance, an improvement of the performance by applying an advanced idea to the vehicle could be achieved by comparing the results with the performance of the original control concept, or a control strategy to extend battery life could be studied with the simulation models. We are currently utilizing the vehicle model in a study that evaluates a number of vehicles according to the technologies, such as electric vehicle, hybrid electric vehicle, plug-in hybrid electric vehicle, and fuel cell vehicle, to predict and optimize the gross vehicle market in the future. Although these concepts are not new in this field, we believe that these studies could produce meaningful results with well-validated simulation models.

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