ABSTRACT

The Prius — a power-split hybrid electric vehicle from Toyota — has become synonymous with the word “Hybrid.” As of October 2010, two million of these vehicles had been sold worldwide, including one million vehicles purchased in the United States. In 2004, the second generation of the vehicle, the Prius MY04, enhanced the performance of the components with advanced technologies, such as a new magnetic array in the rotors. However, the third generation of the vehicle, the Prius MY10, features a remarkable change of the configuration — an additional reduction gear has been added between the motor and the output of the transmission [1]. In addition, a change in the energy management strategy has been found by analyzing the results of a number of tests performed at Argonne National Laboratory’s Advanced Powertrain Research Facility (ARRF). Whereas changes in the configuration, such as the reduction gear, are possibly noticeable, it is not easy to determine the effect of the energy management strategy because the supervisory control algorithm is, generally, not published. Further, it is almost impossible to analyze the algorithm without testing results obtained from a well-designed testing process. On the basis of extensive experience in designing the controllers of power-split hybrid electric vehicles in Autonomie, we could identify the supervisory control algorithm by analyzing the testing results obtained from the APRF. A vehicle model and a control model for the Prius MY10 have been developed to reproduce the real-world behaviors, and the simulation results are compared with the testing results. In the simulation, the developed vehicle model achieves fuel consumption that is close to the testing value, within 5%, and the operation of the engine model was similar to that of the real-world engine.

INTRODUCTION

Toyota launched the first hybrid electric vehicle (HEV), the Prius, and produced it in significant numbers. Although the concept of the power-split device is derived from a classic idea, the innovative design and the sophisticated controller could make the Prius a representative HEV, while new vehicle concepts — such as the Volt from General Motors or the Leaf from Nissan — are emerging as strong competitors. This study is focused on the control strategy of the Prius, especially for the latest version of the vehicle, the Prius MY10. The Prius MY10 arrived more than 10 years after the vehicle entered the U.S. market. However, the control strategy is not well published because the supervisory control algorithm is proprietary to the company, although several studies based on testing results have shown the control concept [2] [3]. While it is possible to analyze the real vehicle’s behavior, doing so requires well-designed testing facilities and experienced engineers who can analyze the testing results. Fortunately, Argonne National Laboratory has such an outstanding testing facility, the Advanced Powertrain Research Facility (APRF), and it has systematic testing processes to obtain reliable testing results. On the basis of the testing results, we could analyze the control algorithm of the vehicle and design a control model in Simulink to reproduce it. The control model is deployed and validated in Autonomie, which is a forward-looking simulation environment based on MATLAB/Simulink and developed to evaluate vehicle’s performance. In this study, all of the steps from testing to validation are briefly introduced, and the comparison between the testing results and the simulation results shows that the developed control model reproduces the real vehicle’s behavior well. The vehicle model for the Prius MY10 could still be improved. For instance, an engine thermal model should be developed to simulate the difference of the control according to the engine temperature, and the engine fuel consumption map does not cover all the operating points because it is generated by testing results obtained only from travels on driving schedules. Nevertheless, this study provides some answers for researchers who are curious about control algorithms for real-world vehicles. Additionally, considering that the energy management strategy of the real vehicle analyzed in this study is based on robust rules rather than on system optimization rules, we also are certain that the performance of the controller could be improved by further studies.
PRIUS MY10: A POWER-SPLIT HEV

The power-split system is able to realize both pure electric driving and hybrid electric driving. The main motor is designed to produce enough power to drive the vehicle, even when the engine does not provide any power at all. Further, the motor recovers the kinetic energy if the vehicle is in regenerative braking mode. The configuration of the system and the differences compared with the previous version will be briefly introduced in this section.

CONFIGURATION

The transmission of the Prius MY10 is realized by two planetary gear sets, whereas the previous version in the Prius MY04, has a single planetary gear set. One of the two planetary gear sets splits the power flow from the engine like the previous version, but the additional gear is operated as a reduction gear for the motor, as shown in Fig. 1 [4] [5].

Although the figure names the electric machines as motor or generator according to primary operation, both the motor and the generator could produce the traction torque or recuperate the energy from the mechanical system. The high-speed permanent magnet synchronous motor is able to produce power up to 60 kW, but the available power for the pure electric driving is less than half of the power because the battery can only provide electric power of 28 kW. One of the differences between the Prius MY10 and the Prius MY04 is that the power levels of the components are increased, as shown in Table 1, which enables the vehicle to achieve improved performance, even though the vehicle becomes heavier than the previous version.

Table 1. Power capacity of the components and vehicle performance of Prius MY10 [5]

<table>
<thead>
<tr>
<th></th>
<th>MY04</th>
<th>MY10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine power (kW)</td>
<td>57</td>
<td>73</td>
</tr>
<tr>
<td>Motor power (kW)</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Net power (kW)</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Fuel economy, sticker (MPG) (City/Highway, combined)</td>
<td>48/45, 46</td>
<td>51/48, 50</td>
</tr>
<tr>
<td>Fuel economy, estimated by daily drivers[10]</td>
<td>47.5</td>
<td>49.2</td>
</tr>
</tbody>
</table>

On the other hand, a planetary gear set added between the output of the transmission and the motor allows the final drive to have a smaller ratio than the Prius MY04. The influence of the change will be discussed in the following section.

PRIUS MY10 VS. PRIUS MY04

The lower ratio of the final drive allows the output of the transmission to have a relatively lower output speed than the previous version [8]. The lower speed at the output means that the generator could have a different speed from the speed of the previous version. One of the drawbacks of the Prius MY04 is that the system efficiency of the vehicle rapidly declines when the vehicle is running on
On the basis of the Prius MY10, we obtained results showing that the conversion loss for the Prius MY10 is reduced by 12% compared with the loss for the Prius MY04 on the Highway Fuel Economy Test (HWFET). On the other hand, we also obtained results showing that the battery in the Prius MY10 is not used as much as the battery in the Prius MY04, as shown in Fig. 3, which is caused by the change of the energy management strategy.

The reduced battery usage could be helpful to extend the lifetime of the battery, but more tests should be conducted to determine the exact influence of the change of the energy management strategy to the battery life. Although the comparison between the two versions is a very interesting topic, it is not a main focus of this study. Instead, we will show the control analysis of the current version and validate it in a forward-looking simulator.

**ANALYSIS OF CONTROL STRATEGY BASED ON TESTING RESULTS**

The control strategy of the vehicle is analyzed by verifying a number of assumptions based on the testing results. For instance, we assumed (1) that the engine is turned on early when the state of charge (SOC) is low or (2) that the regenerative braking power is limited by the temperature of the battery. On the basis of experience, we could list the assumptions in order of priority and verify them by analyzing the testing results. The research facility used to perform the vehicle testing results and analyze the control patterns will be introduced in this section.
VEHICLE TESTING

The APRF is designed for researchers who conduct vehicle benchmarking and testing activities, and a number of studies have been published based on the testing results [2] [3] [6]. The facility is able to run both two-wheel driving tests and four-wheel driving tests, and it can recover important information on vehicle performance, such as fuel economy, energy consumption, and emission output.

![Prius MY10 tested in the Advanced Powertrain Research Facility](image)

The Prius MY10 (Fig. 4) is tested on 25 various driving schedules on the dynamometer, such as one accelerating performance test, six steady-speed tests, and 18 tests on certificated driving schedules. Further, the engine is started at high temperature or low temperature to determine the effects of the engine temperature on the driving performance. For the analysis of the control strategy, the steady speed testing results are primarily used to analyze basic control patterns and to establish control rules. The testing results obtained from various driving schedules are used to verify the established rules.

ANALYSIS OF TESTING RESULTS

In this section, we introduce three main strategies essential for controlling the vehicle from the study. First, the mode decision control is described by the engine on/off condition. Second, the SOC of the battery is the main reference variable to determine the desired battery power. Finally, the engine operation could be explained by a predefined line. The test results are analyzed to obtain these three control strategies.

**Engine-on condition**

The operation of the engine determines the mode, such as pure electric vehicle mode (PEV mode) or HEV mode. The engine is simply turned on when the driver’s power demand exceeds a predefined threshold, as shown in Fig. 5, where the demand power is determined by the pedal signal and the current vehicle speed.
In the figure, the engine is turned on early if the SOC is low, which means that the system is changed from PEV mode to HEV mode to avoid failing the management of the SOC of the battery. On the other hand, the engine is turned on during conditions that are not expected, such as the circles shown in Fig. 5. The circles indicate when the driver requires torque higher than 900 Nm at wheel, which means that the engine provides propulsion power if the motor does not cover the desired performance, even though the power demand is lower than the threshold.

**SOC balancing**

The desired output power of the battery is highly related to the energy management strategy. We found that, when the vehicle is in HEV mode, the battery power is determined by the current SOC, as shown in Fig. 6. The results are obtained by extracting the testing data when the vehicle is in HEV mode and when the effect of target tracking torque is minimized. The motor and generator could consume additional power when they need to trace a target. The testing results are not considered for the control target if a significantly transient dynamic behavior exists in the transmission.
Although some points are out of the trend, the overall trend shows that the energy management strategy tries to bring SOC back to a regular value of 60%. Both the engine on/off control and the battery power control are robust approaches of the Prius MY10 to manage SOC in the appropriate range. If the SOC is low, the engine is turned on early, and the power-split ratio is determined to restore the SOC to 60%, so that the SOC can be safely managed without depletion.

**Engine operation**

The two control concepts previously stated could determine the power-split ratio. The concepts do not, however, generate the target speed or torque of the engine because the power-split system could have infinite control targets that produce the same power. Therefore, an additional control is needed to determine the operating target, for which engine speed operating points are obtained according to the engine power, as shown Fig. 7.

![Engine Operating Targets](image)

*Fig. 7. The engine operating targets (The engine speed is determined by the desired engine power.)*

To obtain the points, we excluded the engine operating points when the engine temperature is low, and instantaneously steady targets are considered only from the testing results, as we did for analyzing the SOC balancing. On the basis of the test data, we assumed that the operating points are supposed to be available when the engine acceleration or deceleration does not exceed $5 \text{ rad/s}^2$ for one second. Although an alternative criterion was possible to extract the steady signal, the filtering parameters were very effective in leaving enough test data to analyze the results.

In this section, we introduce three main concepts for the control strategy by analyzing the testing results. If the power demand is calculated by the pedal, the engine status is determined by the power demand or by the request of the performance. If the engine is turned on, the desired output power of the battery is determined on the basis of the current SOC, and then the engine should provide appropriate power to drive the vehicle. Finally, the engine operating targets are determined by a predefined line, and so the controller can produce required torque values for the motor and the generator on the basis of the engine speed and torque target. The detailed process for the control is introduced in following section.

**CONTROL MODEL**

In general, control models possess two processes — a target generation process and a target tracking process — as shown in Fig. 8. The target generation process creates control targets, which can be based on rules, optimization, or other concepts. On the other hand, the target tracking process adjusts the generated torque targets to trace the target speed.
The analyzed strategies discussed in the previous sections are applied to the target generation process; here, however, we introduce a simple tracking concept, based on a time constant, for the target tracking process.

**TARGET GENERATION**

Fig. 9 shows flows of the control signal for the target generation, in which the three control strategies are utilized to determine the control signal.

The driver power demand is delivered by the pedal position, and the mode of the system is determined by the demand power and the current SOC, as shown in Fig. 5. A simple flow chart for the mode decision is shown in Fig. 10.

In reality, the engine is turned on not only when the power demand from the driver exceeds the threshold, but also when the engine needs to be warmed up because the engine temperature is low. On the other hand, the engine is turned off when the driver takes the foot off the pedal, but the engine speed is sustained at an idle speed without fuel if the vehicle speed is higher than a certain speed, since it is helpful when the engine is turned on again at the high speed. Meanwhile, the other control targets, such as the desired battery power and the target speed and torque of the engine, are simply determined by the concepts described in the previous section. We used those concepts to develop a control model in the target generation process.
TARGET TRACKING

In the target generation, the torque targets for the motor and the generator are calculated on the basis of the equilibrium of the power-split device [7], which means that the generated targets could not trace the optimal target speed of the engine, so an additional control concept is needed to track the targets.

![Diagram of target tracking](image)

*Fig. 11. The target tracking torque for tracing the desired engine speed*

Fig. 11 shows the concept of the target tracking, in which the generator adds a small torque to increase the engine speed, while the motor also produces a small additional torque to compensate for the impact from the transmission. The amount of the additional torque is calculated in real time on the basis of the target, or reference, speed. In the tracking control, we assumed that the engine does not participate in the target tracking process, since the time response of the engine torque is generally 10 times larger than the time response of the electrical machines. Also, we could not find clear proof from the testing results that the engine produces additional torque for the target tracking, whereas the generator and the motor show the tracking torque in the results. Considering that the results obtained from the tests are measured by the sampling time, 0.1 seconds, it is not easy to analyze the exact tracking control algorithm. Therefore, a simple tracking control based on a time constant is designed to realize the supervisory control for the Prius MY10.

![Graph of engine speed response](image)

*Fig. 12. The response of the engine speed (The engine speed rises according to the driver’s power demand, with a small delay. The dynamic response of the behavior can be realized by the time response.)*

The time constant, or a decay constant, is approximated by the response of the engine speed according to the driver’s power demand, as shown in Fig. 12. Although the exact time constant could not be obtained from the testing results, the controller is designed to calculate the additional torque to satisfy an approximated time constant (0.3 seconds). To design the control model for the target tracking based on that time constant, we can consider a dynamic system that satisfies it, which is expressed as:
\[
\dot{S}_{\text{eng}} = \frac{1}{\tau}(S^*_{\text{eng}} - S_{\text{eng}}) \tag{1}
\]

where \(S^*_{\text{eng}}\) and \(S_{\text{eng}}\) are the target speed and the current speed of the engine, and \(\tau\) is the time constant. On the other hand, the dynamic equation for the power-split systems can be expressed as:

\[
\begin{bmatrix}
\dot{S}_{\text{gen}} \\
\dot{S}_{\text{eng}} \\
\dot{S}_{\text{ring}}
\end{bmatrix} + C^{\top}\lambda =
\begin{bmatrix}
T_{\text{gen}} \\
T_{\text{eng}} \\
T_{\text{mot}}
\end{bmatrix}
\tag{2}
\]

where \(J\) is the inertia matrix of the transmission system, and \(C\) and \(\lambda\) are the Jacobian and the Lagrange Multiplier, which could be interpreted as the internal torque vector. In the equation, \(S_{\text{gen}}, S_{\text{eng}},\) and \(S_{\text{mot}}\) are the speed of the generator, the speed of the engine, and the speed of the motor, and \(T_{\text{gen}}, T_{\text{eng}},\) and \(T_{\text{mot}}\) are the additional tracking torques for the generator, the engine, and the motor when the control target torques do not affect the transient dynamic because they satisfy the equilibrium. If we have a transfer matrix, \(B\), which satisfies that:

\[
\begin{bmatrix}
S_{\text{gen}} \\
S_{\text{eng}} \\
S_{\text{ring}}
\end{bmatrix} = B \begin{bmatrix}
S_{\text{gen}} \\
S_{\text{eng}} \\
S_{\text{ring}}
\end{bmatrix}, \tag{3}
\]

the dynamic equation in Eq. (2) can be expressed as:

\[
\begin{bmatrix}
\dot{S}_{\text{eng}} \\
\dot{S}_{\text{ring}}
\end{bmatrix} = \left[B^TJB\right]^+B^T \begin{bmatrix}
T_{\text{gen}} \\
T_{\text{eng}} \\
T_{\text{mot}}
\end{bmatrix}, \tag{4}
\]

because \(B^T\lambda\) is zero. We assumed that the tracking torque from the engine is zero, and the ring gear should not be affected by the tracking torque, and so the equation can be expressed as:

\[
\begin{bmatrix}
\dot{S}_{\text{eng}} \\
0
\end{bmatrix} = \left[B^TJB\right]^+B^T \begin{bmatrix}
T_{\text{gen}} \\
0 \\
0
\end{bmatrix} = \frac{1}{\tau}(S^*_{\text{eng}} - S_{\text{eng}}) \tag{5}
\]

Although there could be a number of solutions that satisfy Eq. (5), we can have the simple tracking torques, which can be expressed as:

\[
\begin{bmatrix}
T_{\text{gen}} \\
T_{\text{mot}}
\end{bmatrix} =
\begin{bmatrix}
C_{\text{gen}} \\
C_{\text{mot}}
\end{bmatrix} \left(S^*_{\text{eng}} - S_{\text{eng}}\right) \tag{6}
\]

where the constant coefficients, \(C_{\text{gen}}\) and \(C_{\text{mot}}\), satisfy that:

\[
\begin{bmatrix}
B^TJB \\
0 \\
0
\end{bmatrix}^+B^T \begin{bmatrix}
C_{\text{gen}} \\
0 \\
C_{\text{mot}}
\end{bmatrix} = \frac{1}{\tau} \tag{7}
\]

The tracking torque is necessary to realize the controller, but it does not significantly affect the vehicle’s performance such as the fuel economy. In general, the additional torque for the generator is very small in the simulation, except when the engine is turned on, or is turned off, as shown in Fig. 13.
The ratio of the tracking torque to the target torque for the motor is even smaller than the ratio of the generator because the motor generally produces a higher torque than the generator. Although the performance of the tracking control could be improved by advanced techniques based on optimal control, such as the Linear Quadratic Regulator [6], the simple tracking control based on the approximated time constant is used for the simulation described in following section. Additionally, the real tracking torque from the test data does not show the peaks as shown in Fig. 13 because the generator torque that we obtained from the test is already filtered by a signal process. An appropriate time constant or an accurate target tracking model better than the current tracking model could be obtained by analyzing the transient behavior of the system.

SIMULATION

The control model mentioned above is deployed and validated in a forward-looking simulator, Autonomie, which has been developed by Argonne National Laboratory for evaluating vehicle’s performances through simulation. In this section, the vehicle model is briefly introduced, and the simulation results show that the developed control model well reproduces the real behavior of the vehicle.

VEHICLE MODEL

Autonomie provides reliable component models that have been validated from a number of testing results, and so our approach is to load the necessary component models for building the Prius MY10 and to apply the developed a vehicle control model (Fig. 14).

While the default model in Autonomie is used for the simulation, the data for the model are generated from the testing data, as shown in Fig. 15.
The motor efficiency map used in the simulation is imported from Oak Ridge National Laboratory [9]. Although the battery of the Prius MY10 is slightly different from the battery of the previous version, the data in the previous model are used for the simulation. Other data, such as vehicle mass, front area, and gear ratio, are obtained from the testing facility.

**SIMULATION RESULTS**

Simulation is done by two certificated driving schedules — the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET) — and the simulation results are compared with the testing results. First, the vehicle speed, the engine speed, and the engine torque on UDDS are compared with the testing results (Fig. 16).

Unfortunately, the engine thermal model is not considered in the developed model, and so the first part of the simulation is not well matched with the testing results because, as we have stated, the engine adheres to different rules when the engine temperature is low. However, the simulation results well reproduce the testing results if the engine is warmed up enough. (After 200s) The other simulation results on HWFET are compared with the testing results, as shown in Fig. 17.
Fig. 17. The simulation results and testing results on HWFET

In the case of HWFET, the engine starts at a high temperature in the test, and so the speed and the torque of the engine well reproduce the testing results even at the start of the driving. In particular, the results show that the engine on/off condition well reproduce the mode change in the Prius MY10.

Fig. 18. The difference between the real test data and the simulation results

In a small range, the results of simulation are, however, slightly different from the results of the real test, especially when the system is under transient dynamics. The engine speed of the real test ranged from 155s to 165s; Fig. 18 shows the transient behavior, although the overall behavior seems to be close to the results of simulation. Further, the engine torque produced from simulation near 175s is not produced in the real test. If additional analyses both for the target generation process and for the target tracking process is done to reduce these differences, the simulation results could be closer to the real test data than the current results.
The SOC obtained from simulation on UDDS is not matched well with the testing results at the first 200 seconds, since the real vehicle tends to maintain the engine turned on to warm up the engine, and so the testing results show an increase in the SOC at the start of the engine. However, the pattern is well matched with the testing results if the engine is hot enough, as in the case of HWFET. On the other hand, the differences in fuel consumption are 3.36% for UDDS and 4.13% for HWFET, which indicates that the simulation could evaluate the vehicle’s performance within 5% (Fig. 18).

**CONCLUSION**

One of advantages for using simulation instead of real-world testing is that the simulation eliminates the effort and costs of evaluating the vehicle’s performance. Further, we could test alternative components or apply advanced control concepts to improve the vehicle’s performance on the basis of simulation techniques. However, the simulator should guarantee the reliability, and the reliability is obtained through an adequate validation process for the models used in the simulator. For this paper, we used a well-known forward-looking simulator. We tried to describe how the simulation models are built and validated for the reliability, and we established that the control model is developed by analyzing a number of testing results. In addition, we verified that the developed control model could well reproduce the testing results. Although the data on engine operation in simulation differ from the test data at low engine temperature, and because the thermal model for the engine is not applied to the simulation, the results obtained from simulation show that fuel economy performance is close (within 5%) and that the operating patterns for other conditions are well matched with those of the real vehicle. Although our study is focused only on the validation of the model in Autonomie, the validated vehicle model should be very beneficial for other studies. For instance, an optimal control concept could be applied to the vehicle model to evaluate the potential performance of the vehicle, and drawbacks or benefits of the real-world control strategy could be explained in the comparison with the optimal case. Meanwhile, an analysis of fuel economies on a number of real-world driving schedules could be possible with the reliable vehicle model. In conclusion, we believe that this study provides useful insight about the real-world control strategy of the Prius MY10, and we hope that researchers can utilize this information.

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