Abstract

Plug-in hybrid electric vehicle (PHEV) has become a candidate for a next hybrid electric vehicle. Because it is able to charge fully with an external electric power source, it can drive as an electric vehicle using only electric motor. European automobile manufacturers producing clean diesel cars have recently developed plug-in hybrid electric vehicles equipped with diesel engine in order to satisfy the regulations of greenhouse gas emissions. Furthermore, dual clutch transmission (DCT) has been developed, an automated manual transmission with dual clutches and two shafts. In case of DCT, different from a manual transmission with one clutch, each clutch automatically prepares operating a following gear for the gear shift, so that it has optimal efficiency in gear shifting.

PHEV can be divided into two modes; charge depleting (CD) and charge sustaining (CS). It is important to distribute required power into an engine and an electric motor properly. How CD and CS are divided becomes the standard of managing the state of charge (SOC), usable capacity of battery. Also, fuel economy depends on the dividing proportions of CD and CS.

This paper proposes a control strategy of power distribution using the slope of the SOC trajectory for plug-in diesel hybrid electric vehicle with DCT. We constructed two simulating models, a detailed model and a simplified model, using MATLAB/Simulink. The slope of the SOC trajectory determines how fast battery is spent in CD mode. Vehicle speed affects fuel economy and changes the slope of the SOC trajectory, so that we applied them on simulating models. To apply on the experiment, the slope of the SOC trajectory was controlled depending on various driving conditions. It is expected that through this study, splitting the predictable driving cycle into CD and CS modes with optimal ratio makes PHEV drive efficiently with high fuel economy.

Keywords: Plug-in diesel hybrid electric vehicle, Diesel engine, Dual clutch transmission, SOC trajectory, Charge depleting mode
1 Introduction

Hybrid electric vehicles (HEV) have been advanced considerably for several years. Recently, automobile manufacturers put forward a scheme on development of plug-in hybrid electric vehicle (PHEV) and their launchings are just around the corner. European makers focus on PHEVs equipped with diesel engine. Although diesel engine is more efficient at low RPM and low torque, motor efficient operating range, than gasoline engine, they have exploited PHEVs integrated as high technology of clean diesel cars. Moreover, regenerative braking power is an important advantage on HEV and PHEV. Since HEV and PHEV have two power sources, engine and motor, many researchers have studied how to distribute demanded propulsive power demanded [1], [2]. Its power management also extends to PHEVs’. Heuristic approaches are easily adapted to real vehicles; rule-based control strategy [3], [4] and Fuzzy logic [5]. Optimal control theories have been applied to PHEVs whose power is distributed. Usually, there are two implements; Dynamic programming (DP) and Equivalent consumption minimization strategy (ECMS). DP is a global optimal control, based on Bellman’s Principle of Optimality [6]. Although it requires much more computability and it is difficult to apply to real-time implementation directly, some authors modify DP [7] or apply to stochastic dynamic programming (SDP) statistically [8], but it is commonly used as a reference, utilized for real-time optimal control or a novel strategy [9]-[14]. Next, ECMS [15], [16] can be implemented in real time, local optimization [17]. A cost function has fuel consumption and virtual fuel consumption, which is minimized to distribute power at instant time. It is important to choose an equivalent factor. This strategy comes near to a global optimal strategy [11], [15], [16]. Many authors have put efforts to implement an online optimal strategy, using a local optimization adjusted on global optimization or estimating future route data, [11]-[14], [17], [18], for example A-ECMS [19].

Basically, PHEV has firstly all-electric range (AER); charge depleting (CD) mode. When the state of charge (SOC) of battery is low, the strategy to maintain a certain level of SOC, which is charge sustaining (CS) mode, should be used. When PHEV takes a rough load, it is efficient that the engine operates optimally with the motor [3]. If trip distance is given for a certain destination and velocity profile is predictable, driving plan should be designed to determine the generating power ratio of engine to motor. In the case when vehicles run for a short distance, it is better to use only electrical source. Previous authors focused on a distance related to energy; engine power or derivative SOC [3], [10]. However, in driving predetermined SOCs, its demanded power can be varied by traffic conditions, user-driving features, and so on. Objective of this paper is proposing a SOC trajectory considering its velocity in time domain.

This research is designed to perform simulating experiments of PHEV with dual clutch transmission (DCT) and it propose a new control strategy using SOC trajectory depending on predicted velocities. The SOC trajectory consists of the slope of SOC at CD mode and constant limit of low SOC. The slope of SOC was analysed with variable velocity profiles. The PHEV model simulating was controlled by SOC trajectory. Based on the results, it is found that using the slope of SOC contributes the improvement of fuel economy.

The paper is organized as follows: Section 2 presents the PHEV model equipped with DCT. Before an optimal control strategy applied to this model is explained, a simplified PHEV model is described. Section 3 describes a rule-based control strategy for PHEV and introduces the slope of the SOC trajectory and it can be called a reference line which determines whether electric mode or hybrid mode is appropriate for PHEV. Section 4 explains how to evaluate PHEV and simulating conditions. The results of simulations are shown in Section 5. Under the condition of a same distance, the simulation results of two different control strategies are compared and analysed. Through analysing the results, we could demonstrate how much fuel economy was improved depending on various velocity profiles. Conclusions are presented in Section 6.

2 Plug-in diesel hybrid electric vehicle model

Configuration of vehicle considered is pre-transmission plug-in hybrid electric vehicle, showed in Figure 1. Because a parallel pre-trans vehicle has engine clutch between engine and motor, it enables pure electric driving by only motor power. It is suitable for PHEV capable to more electric drive.
2.1 PHEV model with DCT

2.1.1 Configuration of PHEV model
Parallel pre-trans PHEV models with auto transmission or auto manual transmission are offered by Autonomie software. DCT is firstly considered to improve performance. It has fast shift quality because there are two driving shafts and two clutches, so that it can prepare gear shift automatically and rapidly as continuous variable transmission. In addition, its energy loss is lower than automatic transmission and thus it recently emerges as an economic transmission. The simulating model simulator was modified that with DCT as shown in Figure 2.

2.1.2 Integrated controller
DCT consists of two parts: dual clutches and gearbox. Transmission controller has determined previous gear ratio and next gear ratio depending on virtual diver’s demand and vehicle speed [20]. PHEV controller selects EV and HEV mode. Their controllers are based on Autonomie. It is important to combine two controllers.

2.2 Simplified PHEV model
The PHEV model is difficult to simulate the long distance-driving cycle. It is necessarily simplified.

2.2.1 Vehicle modelling and longitudinal vehicle dynamics
Simplified PHEV model consists of dynamic models of each component and inertia. 

The engine driving torque $T_e$ is applied to the clutch.

$$T_e - T_{c1} = I_e \alpha_e$$

(1)

Where $T_{c1}$, $I_e$, and $\alpha_e$ represent the clutch input torque, the engine inertia, and the angular acceleration of engine, respectively.

Considering the inertia of clutch, $I_c$, the output clutch is formulated as:

$$\eta_c T_{c1} - T_{c2} = I_c \alpha_c$$

(2)

Where $\eta_c$, $T_{c2}$, and $\alpha_c$ are the efficiency of clutch, the output torque of clutch, the angular acceleration of clutch, respectively. 

In HEV mode, since the motor is also propulsion, the torque by engine and the motor torque $T_m$ is applied to the transmission.

$$T_m + T_{c2} - T_i = I_m \alpha_m$$

(3)

Where $T_i$, $I_m$, and $\alpha_m$ are the transmission received by the power source, the inertia of motor, and the angular acceleration of motor, respectively. The gearbox is modelled by a pair of gears with ratio of $N_t$ which is the ratio determined by the acceleration pedal system and the actual velocity.

$$\eta_t N_t T_i - T_d = I_t \alpha_t$$

(4)

Where $\eta_t$, $T_d$, $I_t$, and $\alpha_t$ are the efficiency of transmission, the driving torque, the inertia of transmission, and the angular velocity of transmission.
The driving torque is distributed equally into two wheels by a differential gear.

\[
\frac{1}{2} \eta_d N_d T_d - T_w = \frac{1}{2} I_d \alpha_w \tag{5}
\]

Where \( \eta_d \), \( N_d \), \( T_w \), \( I_d \), and \( \alpha_w \) are the efficiency of the differential gear, the ratio of the gear, the torque of wheel, the inertia of the gear, and the angular velocity of wheel.

The two wheel torque applies the tractive force, \( F_x \).

\[
T_w - \frac{1}{2} F_x R_i = I_w \alpha_w \tag{6}
\]

Where \( R_i \), \( I_w \), and \( \alpha_w \) are the wheel’s radius, the inertia of wheel, and the angular velocity of wheel.

Finally, the vehicle tractive force is calculated as the longitudinal dynamics equation:

\[
Ma = F_x - (F_{\text{drag}} + F_{\text{roll}} + F_{\text{grade}}) \tag{7}
\]

2.2.2 Engine and motor model

Engine and motor consist of their characteristic maps by scaling the wide open throttle torque – speed map, Brake specific fuel consumption (BSFC) of diesel engine, motor characteristic map (maximum torque – speed) and electric efficiency map of motor.

2.2.3 Battery model

Battery has an internal resistant \( R_b \) and open circuit voltage \( OCV \), which are determined by battery SOC. Figure 3 shows a basic circuit of battery based on Kirchhoff’s voltage law [21]:

\[
V_b = OCV - i R_b \tag{8}
\]

Where \( V_b \) and \( i \) are the voltage and the current of battery, respectively. Its current consists of that of motor/generator \( (i_{M/G}) \) and ISG \( (i_{\text{ISG}}) \).

\[
i = i_{M/G} + i_{\text{ISG}} \tag{9}
\]

The sign of motor/generator current \( (i_{M/G}) \) is determined by the motoring and generating of power. When its sign is positive, the battery is discharging and the motor generates the power of driving. Otherwise, it is charging and the motor function as generator.

\[
i_{M/G} = \frac{P_{M/G}}{V_b} \tag{10}
\]

Where \( P_{M/G} \) is the power of motor/generator. The estimated battery SOC is formulated as:

\[
SOC = SOC_{\text{initial}} - \frac{\int i \, dt}{Capacity_{\text{max}}} \tag{11}
\]

2.2.4 Integral starter and generator (ISG)

The engine can recharge the battery to follow the slope of SOC trajectory by generating integral starter and generator (ISG). However, the engine consumes more fuel in unnecessarily operating situation and the efficiency of energy conversion is low, which is a complex process; because engine operates by fuel, chemical energy (fuel) is converted into mechanical energy (engine) and it is converted into electrical energy (ISG). Further, to operate motor by using this energy, electric energy should be converted into mechanical energy. It is inefficient to charge battery by engine. In this paper, ISG does function as a starter.

2.2.5 Simplified PHEV simulator

A simplified PHEV simulator consists of battery, ISG, engine, engine clutch, motor, transmission, final reduction gear, and vehicle dynamics model as shown in Figure 4. As engine clutch is disengaged, the motor only generates energy for pure-electric driving.

2.3 Vehicle model specification

There are values of its components, engine, motor, transmission, and battery as indicated in Table 1. A class of the vehicle is midsize PHEV sedan. Engine is diesel 4 cylinder DOHC.
Table 1: Specification of PHEV and simulation parameters and values

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>Type</td>
<td>Diesel</td>
</tr>
<tr>
<td></td>
<td>Maximum power</td>
<td>65 kW</td>
</tr>
<tr>
<td></td>
<td>Speed range</td>
<td>1000-4000 RPM</td>
</tr>
<tr>
<td>Motor</td>
<td>Maximum power</td>
<td>60 kW</td>
</tr>
<tr>
<td></td>
<td>Speed range</td>
<td>0 – 6000 RPM</td>
</tr>
<tr>
<td>Transmission</td>
<td>Type</td>
<td>DCT</td>
</tr>
<tr>
<td></td>
<td>Gear ratio</td>
<td>6 speed</td>
</tr>
<tr>
<td>Battery</td>
<td>Type</td>
<td>Li-ion</td>
</tr>
<tr>
<td></td>
<td>Capacity</td>
<td>37 Ah</td>
</tr>
<tr>
<td></td>
<td>Cell number</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Nominal Voltage</td>
<td>360 V</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Vehicle mass</td>
<td>1720 kg</td>
</tr>
<tr>
<td></td>
<td>Frontal area</td>
<td>2.25 m²</td>
</tr>
<tr>
<td></td>
<td>Drag coefficient</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Rolling resistance coefficient</td>
<td>0.014</td>
</tr>
</tbody>
</table>

3 Control strategy for PHEV

3.1 Basic PHEV mode selector

3.1.1 Mode select on demanded torque and SOC

PHEV supervisory control consists of EV, HEV, Engine only mode depending on SOC level and demanded torque. When SOC is above SOC limit, CD mode starts and otherwise, CS mode does. Predicted velocity profile makes a SOC trajectory which determines EV, HEV, and Engine only mode. Figure 5 is the flow chart of mode selecting algorithm.

3.2 Power distribution strategy

3.2.1 Rule-based control strategy

When SOC is high, motor can only propel the vehicle. Otherwise, both engine and motor operate properly as its power sources meet the demanded power of a vehicle. In CD mode, motor is used as a power source as a pure electric vehicle except that the road load is high. When battery SOC reaches a limitation level, battery sustains a certain level in order to prevent its malfunction [1]. Engine and motor cooperate efficiently in charge sustaining (CS) mode.

3.2.2 Control strategy with the slope of SOC trajectory

A slope of SOC trajectory extends the usage of motor to all driving. Like CS mode, the slope of SOC limit is used to distribute engine and motor power. It enables motor to operate for the duration of demanded driving range. The slope is defined as

$$\alpha = \frac{SOC_{\text{max}} - SOC_{\text{limit}}}{\tau_{SOC}}$$  \hspace{1cm} (12)

$SOC_{\text{max}}$ is the maximum battery SOC and $SOC_{\text{limit}}$ is a limit level of battery SOC. $\tau_{SOC}$ is
time for estimated velocity profile. By combining CD and CS mode, SOC trajectory is formulated as

\[ SOC_{\text{trajectory}} = SOC_{\text{instant}} - \alpha \times t \quad (13) \]

\( SOC_{\text{instant}} \) is instant SOC of the moment to estimate velocity profile and \( t \) is time.

Figure 6 shows results of SOC simulating the vehicle between rule-based control and SOC trajectory control. A magenta dotted line is SOC trajectory \( (SOC_{\text{trajectory}}) \) and a blue solid line is SOC result. The SOC result follows the SOC trajectory well.

If the slope of SOC is gradual, CD mode range extends and it becomes as a conventional HEV. However, a horizontal slope of SOC is meaningless because PHEV gets energy from motor frequently or it obtains energy from two sources at the optimal ratio between two for higher fuel economy. Therefore, an optimal slope needs to be defined.

4 Evaluation for PHEV

PHEVs are usually compared with conventional fuel vehicles in terms of their price. Battery is still expensive for PHEVs. It has an advantage of having high fuel economy over conventional vehicles.

4.1 Fuel economy

Fuel economy of HEV can easily be evaluated as initial and final SOC are equal [24]. However, the evaluation of PHEVs’ fuel economy is different from conventional hybrid electric vehicles. Since the vehicle runs a long distance, battery SOC falls down to the level, which is not recuperated by regenerative braking power to the initial SOC.

Illustrated graphically in Figure 7 is the demanded driving cycle and actual vehicle speed by repeating four times UDDS.

\[ FC(l) = \text{fuel density}(l/g) \times \int \text{fuel rate}(g) dt \quad (14) \]

Where \( FC \) is fuel consumption (fossil fuel).

\[ FE_{\text{equivalent}} = \frac{\text{Distance(km)}}{FC(l) + E_{\text{elec}} / E_{\text{equivalent}}} \quad (15) \]

Where \( FE_{\text{equivalent}} \) is fuel economy with both fuel and electric energy. \( E_{\text{elec}} \) represents consumption of battery, and \( E_{\text{equivalent}} \) means a certain value to convert \( E_{\text{elec}} \) into equivalent volume of fossil fuel. Evaluating fuel economy of PHEV is recommended in SAE J1711 [23], [24]. The driving cycle is repeated by the time when SOC reaches the limit of CS mode. However, in this paper, the control strategy of SOC trajectory can expand or reduce a range of CD mode. It makes that fuel economy cannot be evaluated by the recommended practice. Its evaluation of fuel economy is an alternative method. It is assumed that fuel economy is estimated at a same driving distance no matter what control strategy is. It is more realistic because fuel economy many drivers see is not officially evaluated but on driving. Figure 7 and 8 are four repetitions of the UDDS and SOC results of different control strategy respectively.
4.2 Cost
Because PHEVs use electric source and fossil fuel, its cost is calculated by the sum of both sources’ cost. We evaluate its cost from EIA (U.S. Information Administration). U.S. on-highway diesel fuel price is $3.281 per gallon (12/22/2014) [25] and the price of electric power is 10.24 cents per kWh; the mean U.S retail price of electricity to ultimate customers by end-use sector on transportation (October 2014) [26]. Fuel and electricity usage are measured and it is converted by total cost ($).

\[
\text{Cost} = FC \times (\text{Cost / gallon}) + \Delta SOC \times Cap \times (\text{Cost / kWh})
\]

(16)

\[
\Delta SOC = SOC_{\text{initial}} - SOC_{\text{final}}
\]

(17)

Where FC is fuel consumption and Cap is capacity of battery. \(\Delta SOC\), \(SOC_{\text{initial}}\), and \(SOC_{\text{final}}\) are SOC variation, initial SOC, and final SOC by all driving cycle.

5 Simulation results

5.1 Simulation conditions
A limit level SOC is the starting of CS mode, 0.3. Initial battery SOC is 0.9.

5.2 Comparison of control strategies

5.2.1 Various desired driving cycle
We simulate two control strategy, the rule-based control and the control strategy of SOC trajectory with the five driving cycles; NEDC (New European Driving Cycle), UDDS (Urban Dynamometer Driving Schedule), LA92, US06, and HWFET (Highway Fuel Economy Driving Schedule).

<table>
<thead>
<tr>
<th>Driving cycle</th>
<th>NEDC</th>
<th></th>
<th>Cost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average speed: 26 km/h</td>
<td>driving range: 11.02 km</td>
<td></td>
</tr>
<tr>
<td>Number of driving cycle</td>
<td>Distance (km)</td>
<td>Fuel economy (%)</td>
<td>Cost (%)</td>
</tr>
<tr>
<td>4</td>
<td>44.09</td>
<td>2.43</td>
<td>-2.10</td>
</tr>
<tr>
<td>5</td>
<td>55.11</td>
<td>4.91</td>
<td>-4.36</td>
</tr>
<tr>
<td>6</td>
<td>66.13</td>
<td>4.04</td>
<td>-3.38</td>
</tr>
<tr>
<td>7</td>
<td>77.16</td>
<td>1.92</td>
<td>-1.74</td>
</tr>
<tr>
<td>8</td>
<td>88.18</td>
<td>2.67</td>
<td>-2.49</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Driving cycle</th>
<th>UDDS</th>
<th></th>
<th>Cost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average speed: 31.5 km/h</td>
<td>driving range: 11.99 km</td>
<td></td>
</tr>
<tr>
<td>Number of driving cycle</td>
<td>Distance (km)</td>
<td>Fuel economy (%)</td>
<td>Cost (%)</td>
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<tr>
<td>3</td>
<td>35.97</td>
<td>-2.31</td>
<td>2.01</td>
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<td>4</td>
<td>47.96</td>
<td>2.31</td>
<td>-2.25</td>
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<td>5</td>
<td>59.95</td>
<td>1.55</td>
<td>-1.47</td>
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<td>6</td>
<td>71.94</td>
<td>-0.58</td>
<td>0.61</td>
</tr>
<tr>
<td>7</td>
<td>83.93</td>
<td>-0.60</td>
<td>0.66</td>
</tr>
<tr>
<td>8</td>
<td>95.92</td>
<td>1.40</td>
<td>-1.35</td>
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</table>
Table 4: Analysis of LA92

<table>
<thead>
<tr>
<th>Number of driving cycle</th>
<th>Distance (km)</th>
<th>Fuel economy (%)</th>
<th>Cost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>47.39</td>
<td>0.40</td>
<td>-0.43</td>
</tr>
<tr>
<td>4</td>
<td>63.19</td>
<td>-0.23</td>
<td>0.24</td>
</tr>
<tr>
<td>5</td>
<td>78.99</td>
<td>-0.67</td>
<td>0.69</td>
</tr>
<tr>
<td>6</td>
<td>94.78</td>
<td>0.16</td>
<td>-0.15</td>
</tr>
<tr>
<td>7</td>
<td>110.6</td>
<td>0.41</td>
<td>-0.39</td>
</tr>
<tr>
<td>8</td>
<td>126.4</td>
<td>-0.13</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 5: Analysis of US06

<table>
<thead>
<tr>
<th>Number of driving cycle</th>
<th>Distance (km)</th>
<th>Fuel economy (%)</th>
<th>Cost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>38.66</td>
<td>-0.86</td>
<td>0.81</td>
</tr>
<tr>
<td>4</td>
<td>51.55</td>
<td>-0.98</td>
<td>0.92</td>
</tr>
<tr>
<td>5</td>
<td>64.43</td>
<td>-1.98</td>
<td>1.97</td>
</tr>
<tr>
<td>6</td>
<td>77.32</td>
<td>-1.73</td>
<td>1.69</td>
</tr>
<tr>
<td>7</td>
<td>90.21</td>
<td>-1.28</td>
<td>1.29</td>
</tr>
<tr>
<td>8</td>
<td>103.1</td>
<td>-1.57</td>
<td>1.55</td>
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</tbody>
</table>

Table 6: Analysis of HWFET

<table>
<thead>
<tr>
<th>Number of driving cycle</th>
<th>Distance (km)</th>
<th>Fuel economy (%)</th>
<th>Cost (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>49.52</td>
<td>-6.98</td>
<td>7.3</td>
</tr>
<tr>
<td>4</td>
<td>66.03</td>
<td>-6.25</td>
<td>6.59</td>
</tr>
<tr>
<td>5</td>
<td>82.53</td>
<td>-5.43</td>
<td>5.66</td>
</tr>
<tr>
<td>6</td>
<td>99.04</td>
<td>-1.23</td>
<td>1.25</td>
</tr>
<tr>
<td>7</td>
<td>115.5</td>
<td>-0.32</td>
<td>0.36</td>
</tr>
<tr>
<td>8</td>
<td>132.1</td>
<td>-0.29</td>
<td>0.27</td>
</tr>
</tbody>
</table>

5.2.2 Analysis

As the slopes of SOC trajectories are changed, fuel economy varies depending on velocity profiles at a same distance. The analysed results are indicated in Table 2-6. There are results of SOC for the repetition of UDDS in Figure 9. In NEDC, at a low average speed, the SOC trajectory control enables more efficient driving regardless of the distance, improving fuel economy and reducing cost. In other hands, in US06 or HWFET, high average speed, the control aggravates fuel economy and increase more driving cost. However, if it uses initially much electric energy, engine and motor does not efficiently operate in case of requiring motor power. Although its strategy is poor at high speed, it is advantageous to prepare electric power later. Consequently, it is more efficient to use the slope of SOC control at a speed of less 30km/h definitely. But, in case of 30km/h speed, it is important to choose a proper slope at that speed. Therefore, this control strategy should be properly used in a velocity range of a vehicle between 30km/h and 40km/h.

5.3 Application to velocity profile

At the moment updating the velocity profile, SOC instant is renewed and the slope of SOC trajectory is altered by instantly estimated velocity profile. Figure 10 shows that two points changes the slope of SOC trajectories as the three velocity profiles. In Figure 11, magnifying the results at break point of SOC trajectory, there is a renewal of a SOC trajectory at 1531 sec. This can be applied to a vehicle, being able to predict velocity profile later.
Figure 12: SOC results by different strategy at DC2-1

Table 10: Results of DC2-1 simulation by the detail PHEV

<table>
<thead>
<tr>
<th></th>
<th>Rule-based</th>
<th>SOC trajectory</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel economy (km/l)</td>
<td>26.34</td>
<td>27.27</td>
<td>3.52%</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>4.14</td>
<td>4.01</td>
<td>-3.00%</td>
</tr>
</tbody>
</table>

Figure 13: Operating points of motor/generator with rule-based (a) and SOC trajectory control strategy (b)

Figure 14: Operating points of engine with rule-based (a) and SOC trajectory control strategy (b)

5.3.1 Complex driving cycle
To evaluate the control strategy of SOC trajectory, new combined driving cycles made of four driving cycle were analysed. The first driving cycle (DC1) consists of UDDS(2), US06(2), LA92(2); the second driving cycle (DC2), HWFET(2) + UDDS(2) + LA92(2); the third driving cycle (DC3), LA92(2) + UDDS(2) HWFET(2). The control strategy of SOC trajectory applies three driving cycles. In Table 7-9, there are three driving cycles and the simulation results. At DC3, its fuel economy was improved 2.45% by the control of SOC trajectory, compared to rule-based control strategy. Furthermore, the reducing rate of cost is -2.36%. Its SOC results are shown as different strategy in Figure 10. Other simulation results also improve fuel economy and reduce cost rather than rule-based strategy as shown in Table 8-9.

5.3.2 Simulation of the detailed PHEV model
The detailed PHEV with DCT model is controlled by two strategies above. Driving cycle is the second modified driving cycle (DC2-1);
HWFET(3) + UDDS(3) + LA92(3). Their slope is selected to the optimal slope analysed before. Simulation results are shown in Figure 12 and Table 10. On the rule-based strategy, battery SOC slowly decreases compared to that of Figure 8, where the engine intervenes in even CD mode in requiring high torque rigorously.

5.3.3 Operating points of engine and motor for two control strategies
Simulation condition is same as Section 5.3.2., above. In Figure 13, operating points of motor are similar, regardless of two strategies, but operating points of engine vary with their strategy. In Figure 14, operating points of engine decrease at low torque-high RPM range, controlled by the SOC trajectory, which is compared with that of the rule-based strategy. Engine and motor are engaged with the engine clutch, where engine prepares to generate alertly even when engine torque is not demanded because of low battery SOC. Its low torque-high RPM range uses more fuel. Brake specific fuel consumption (BSFC) is an index of measuring fuel efficiency. Therefore, SOC trajectory controller operates engine more efficiently with motor and improve fuel economy and reduces operating cost.

5.4 Gasoline and Diesel engine operation

5.4.1 Operating points of engine and motor for different engine types
Comparison of gasoline and diesel engine intends to analyse PHEV related to engine type. Two engines have the same maximum power, 65kW, but different maximum torque and speed range. Two PHEVs drive 9 times UDDS repeatedly on being controlled by SOC trajectory; their motors have the same capacity. Two models are equipped with DCT. Figure 15 shows operating points of engine. Diesel engine operates more efficiently than gasoline engine which does not utilize high efficient range. Even if UDDS is urban cycle and no higher velocity exists, PHEV with diesel engine runs more efficiently at CD mode as shown in Table 11. However, gasoline price is lower than that of diesel. It is reverse in terms of their cost, where gasoline price is $2.403 per gallon (12/22/2014) [25].

6 Conclusions
This paper proposes a control strategy of SOC trajectory for parallel pre-transmission plug-in hybrid electric vehicle with DCT, aimed at improving the fuel economy of PHEVs. The vehicle was distributed the engine and the motor power by following the SOC trajectory predetermined by a velocity profile. Depending on predicting new velocity profiles, the optimal SOC trajectories should be applied. The simplified vehicle model simulator was constructed and the various velocity profiles were analysed with the
SOC slope using this model. Each optimal slope of SOC forms the velocity profiles. The model controlled by SOC trajectory can drive with high fuel economy compared to rule-based strategy. In addition, its strategy was applied to the detailed PHEV with DCT and it showed that demanded power is more efficiently distributed to the required driving range. Finally, their fuel economy and driving cost are compared depending on the types of engine.

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