Control Strategy to Improve Fuel Economy for Plug-in Hybrid Electric Vehicle considering Degree of Driver Aggression

S. Lee1, J. Choi1, S. Park1, J. Pi1, H. Shin1, K. Jeong2 and H. Kim1
1School of Mechanical Engineering, Sungkyunkwan University, Suwon-si, Republic of Korea, c208@naver.com
2Intelligent Control System R&D center, Korea Automotive Technology Institute, 303Pungs-ro, Pungse-myeon, Dongnam-gu, Cheonan-si, Republic of Korea, kyjeong@katech.re.kr

Abstract
In this study, a control strategy to improve the fuel economy was proposed for a PHEV (plug-in hybrid electric vehicle) considering driver tendency. To identify the driver tendency, a driver model which reflects the driver tendency was developed using the driving data. The target PHEV model was developed based on MATLAB/Simulink and validation of the vehicle model was performed by experiments. From the driving data, the driver model which can reflect the driver tendency was developed. To describe the driver tendency, degree of driver aggression (DDA) was proposed, which was determined by fuzzy logic. Using the DDA, a PHEV control algorithm was proposed to improve the fuel economy, which consists of the engine on/off and battery charge-engine operation. The engine on/off control reduces frequent engine on/off for a high DDA (wild driver), whereas the battery charge-engine operation controls the engine operation by considering both the engine thermal efficiency and powertrain efficiency to maintain the battery SOC. It is expected that proposed control algorithm provides improved fuel economy of the target PHEV.

Keywords: DDA (Degree of Driver Aggression), PHEV (Plug-in Hybrid Electric Vehicle), VIDE (Virtual Integrated Development Environment), Fuel economy

1 Introduction
Recently, the oil price falls to $50~60 per barrel due to the supply of the shale gas and the increase of the oil production[1]. Nevertheless, it is unavoidable to shift the energy paradigm from the fossil energy to the electric energy, considering the restricted fossil resources and the environmental issue. The PHEV (plug-in hybrid electric vehicle) that uses the internal combustion engine and the battery with a plug is expected as a viable solution to meet these requirements. The PHEV can run only by the motor in EV mode using the home electricity and extend the travel distance by operating the engine in HEV mode. Since the fuel economy of the PHEV depends on its configuration and control strategy, various studies were performed to improve the PHEV efficiency in the vehicle level as well as in the component level[2][3]. However, the fuel economy is more influenced by the tendency of driver, rather than uncontrollable factors by drivers such as driving mode or surrounding environment[4]. In the hybrid vehicle, if the tendency of driver is wild, then the driver’s
acceleration/deceleration intent changes large thereby the mode change(EV/HEV) occurs frequently. This causes increase in the electric energy loss to start the engine due to the frequent engine on/off[5][6]. A study on optimization of increasing the fuel economy under extreme conditions to maintain the battery SOC(state of charge) by controlling change condition between EV and HEV modes according to driving mode(city/highway), tendency of driver(wild/mild), and surrounding environments(temperature/altitude/gradient) was performed[7]. If the battery SOC is nearly flat, the demanded vehicle power is produced by only the engine, in which advantages of hybrid electric vehicle are lost. As a result, a study on improving the engine efficiency while charging a battery when a battery SOC is low or flat is needed. In addition, if driver’s tendency is wild, fuel efficiency decreases due to the large consumption of battery and frequent mode change[7].

In this study, the engine control algorithm was proposed to improve the fuel efficiency of PHEV in consideration of the driver tendency.

2 Modeling of PHEV powertrain system and development of performance simulator

In this study, plug-in Prius was selected as a target PHEV. Fig. 1 and Table 1 show the configuration of the target vehicle. The vehicle simulator was developed based on MATLAB/Simulink. Fig. 2 shows the validation results of the vehicle simulator for driving FTP-72 cycle. In Fig. 2, vehicle velocity, battery SOC, MG1 torque, MG1 speed, MG2 torque, MG2 speed, engine speed, and engine torque are compared. The simulation results are in good agreement with the test results, which demonstrate the validity of the vehicle simulator.

3 Analysis of fuel economy according to the driver model and the driver tendency

Driver model to reflect the driver tendency was developed using the driving data which were obtained from VIDE(virtual integrated development environment). The VIDE is a virtual driving environment, which can evaluate the performance of the vehicle component in the vehicle level. The VIDE was developed using the 3D rendering tool which can simulate the road condition, traffic signal system and weather[11]. To apply the actual driver tendency to the driver model, vehicle speed, Ap(accel pedal), Bp(brake pedal) were collected by driving the UDDS(urban dynamometer driving schedule) which is provided by EPA(United States Environmental Protection Agency) by using VIDE. Fig. 3 shows the VIDE
including the screen of VIDE, and the main GUI. In the main GUI, the user can select the vehicle type, the vehicle platform, and the simulation condition. In this test, 8 drivers participated who have driver license and driving experience. The screen of VIDE shows real-time vehicle speed, battery current, fuel economy, etc. 8 drivers conducted the test in following the velocity profile within ±3 km/h error.

Driver’s characteristics are divided into reckless, sensitive, and unskilled. ‘Reckless’ and ‘sensitive’ are especially more influential to the fuel economy than unskilled driving[12]. Therefore, reckless and sensitive are selected as factors of driver tendency which are able to represent actual driver. Fig. 4 shows the driver model(A) which is modeled by the proportional integral controller.

In Fig. 4, the driver model consists of \( K_p \) (proportional control gain), \( K_i \) (integral control gain), \( D(t) \) is the demanded velocity, \( V(t) \) is the vehicle speed, \( e(t) \) is the error between demanded velocity and vehicle speed, which is calculated by \( D(t)-V(t) \), \( U(t) \) is the control signal of \( A_p, B_p \) which are input to the vehicle through the proportional integral controller. \( A_p, B_p, \) vehicle speed, and demanded velocity are collected by using VIDE to obtain \( K_p, K_i \) which reflect actual drivers. Through \( A_p, B_p, \) vehicle speed, and demanded velocity, the following equations are derived to obtain \( K_p, K_i \).

\[
\begin{align*}
U(t) &= K_p \cdot e(t) + K_i \cdot \int_{t-1}^{t} e(t) \, dt \\
U(t+1) &= K_p \cdot e(t+1) + K_i \cdot \int_{t}^{t+1} e(t) \, dt \\
K_p &= \frac{U(t) - \int_{t-1}^{t} e(t) \, dt}{\int_{t-1}^{t} e(t) \, dt} \cdot U(t+1) \\
K_i &= \frac{U(t) - \int_{t-1}^{t} e(t) \, dt}{\int_{t-1}^{t} e(t) \, dt} \cdot \frac{e(t)}{e(t+1)} \cdot U(t+1) \\
&\quad \int_{t-1}^{t} e(t) \, dt = \frac{e(t)}{e(t+1)} \cdot \int_{t}^{t+1} e(t) \, dt
\end{align*}
\] (1) (2)

Figure 2: Validation results of target vehicle simulator
The driver model is derived from the average values of $K_p$ and $K_i$ over the entire driving cycle via the collected data. To determine the tendency of driver in the driver model, $K_p$ and $K_i$ of each driver are applied to the driver model of the target PHEV simulator and simulations are performed for the FTP-72 and US06 driving cycles. From the simulation, mean values of change rate of $U(t)$, which is a control signal input to the vehicle by a driver, and number of crossing between $A_p$ and $B_p$ are obtained. A mean values of change rate of $U(t)$ is calculated as,

$$\frac{\int_0^t \frac{\partial}{\partial t} U(t) \, dt}{t}$$

(3)

Since the driver tendency is relative, in this study, a wild driver is defined as a driver who has larger change rate of $U(t)$ and crossing times of $A_p$ and $B_p$ than other drivers. The opposite is a mild driver.

Before performing comparison of fuel economy by drivers, it is necessary to calculate an equivalent amount of fuel of electric energy and represent as a fuel economy of km/l.

$$E_f = \frac{\Delta m_{fuel}}{\rho_{fuel}}$$

(5)

where $D$ is the driving distance, $SOC_{initial}$ is the battery initial SOC, $SOC_{final}$ is the battery final SOC, $\Delta m_{fuel}$ is the engine fuel consumption, $\rho_{fuel}$ is the fuel density, and $Q$ is the battery capacity.

The equivalent fuel economy is compared according to diver tendency. In the simulation, the OOL control is applied. The OOL control is a method to control the engine to follow the OOL that has the highest fuel efficiency.

<table>
<thead>
<tr>
<th>Table 2: Fuel economy comparisons between mild driver and wild driver</th>
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<tbody>
<tr>
<td>Driver</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>Driver 2</td>
</tr>
<tr>
<td>Driver 3</td>
</tr>
<tr>
<td>Driver 6</td>
</tr>
<tr>
<td>Driver 8</td>
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</tbody>
</table>

In Table 2, comparison results of equivalent fuel economy are shown according to driver tendency using the OOL control. The result shows that the fuel economy of Driver 6, 8 who represent wild driver is lower than Driver 2, 3 who represent mild driver during FTP-72 cycle driving.

4 Driver tendency determination

It is difficult to determine an objective standard to evaluate the driver tendency due to the relativity of driver tendency. In addition, driver tendency may change depending on the road or traffic condition. In order to evaluate the indetermination that is difficult to be decided by objective standard, a fuzzy logic is used. The mean value of $A_p$, $B_p$ and mean value of change rates of $A_p$ and $B_p$ which
are input signals to the vehicle are selected as the input variables of fuzzy logic. In the fuzzy logic, Gaussian curve membership function was used. The max-min method of Mamdani is used for fuzzy logic and the centroid method is used for defuzzification. Fig. 5 represent the DDA(degree of driver aggression) per driver using fuzzy logic. The result value of DDA represents the driver tendency. The wild driver’s DDA is close to 1 and the mild driver’s DDA is close to 0.

![Figure 5: Aggression of each driver](image)

Fig. 6 shows the time response of the vehicle parameters according to DDA. As shown in Fig. 6(a), the wild driver(DDA=0.774) and mild driver(DDA=0.448) have the almost same driving velocity. But, the wild driver’s battery SOC rapidly decreases because the wild driver has a large value of acceleration and deceleration in low speed region using EV mode(b). If the battery SOC decreases to the lower limit, the engine begins to operate to produce the demanded vehicle power. In addition, the wild driver shows larger Ap and frequent change of Ap(c) compared with those of the mild driver. Therefore, the demanded vehicle power changes frequently thereby having a frequent engine on/off(d).

5 PHEV control algorithm according to driver tendency

5.1 Engine on/off control

Fig. 7 shows the engine on/off control strategy considering DDA. As shown in Fig. 7, the wild driver(DDA=0.774) has larger value and more frequent change of demanded vehicle power than mild driver(DDA=0.448). Therefore, the purpose of control is to reduce the excessive engine on/off by using different engine on/off condition for DDA=0.448 and DDA=0.774. Demanded vehicle power and braking power are determined by Ap and Bp. So Ap threshold value during the engine on and Bp threshold value during the engine off are obtained using a weight factor for the engine on/off condition control according to driver tendency.

![Figure 6: Simulation results for FTP-72 cycle](image)

![Figure 7: Engine on/off control strategy](image)

5.2 Battery charge-engine operation control to maintain a battery SOC

Fig. 8 represents the engine operation strategy for battery charge. The engine output should be larger than the demanded vehicle power to charge a battery. However, the PTE(powertrain efficiency) control produces the same power as the demanded
power from the engine. The PTE control was proposed by considering the transmission efficiency as well as the engine thermal efficiency[14]. In this study, the engine is controlled to be operated at the point of satisfying both of the engine operation for the PTE control and the engine operation to charge the battery as shown in Fig. 8(C). An appropriate battery charging amount should be determined since the actual fuel economy is reduced due to the efficiency of the motor/generator and efficiency of battery charging and discharging[15]. The additional power is added to the engine demanded power through the weight factor to maintain a battery SOC according to the DDA. The engine is controlled to be operated at Fig. 8(B) whose weight factor is 0. For DDA=0.3~0.8, the engine is controlled to increase the engine power from Fig. 8(B) to (C) as increasing of the weight factor. If the weight factor is 1, the engine is controlled to be operated at Fig. 8(C).

Table 3: Comparison of equivalent fuel economy for DDA control and OOL control

<table>
<thead>
<tr>
<th></th>
<th>Equivalent fuel economy</th>
<th>Improvement ratio [%]</th>
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</thead>
<tbody>
<tr>
<td>OOL control</td>
<td>[km/l]</td>
<td>DDA control</td>
</tr>
<tr>
<td>Driver 6</td>
<td>13.6</td>
<td>15.1</td>
</tr>
<tr>
<td>Driver 8</td>
<td>12.2</td>
<td>14.5</td>
</tr>
<tr>
<td>Average</td>
<td>12.9</td>
<td>14.8</td>
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</table>

7 Conclusion

An engine on/off and engine operation control algorithms were proposed by considering the driver tendency. To determine the driver tendency, the driving data of various driver were collected using VIDE(virtual integrated development environment). The driver model was developed based on the collected driving data. Using the driver model, simulations were performed and the mean value of Ap, Bp, mean value of change rate of Ap, Bp, and number of cross between Ap and Bp were obtained. Using these data as the input of a fuzzy logic, DDA(degree of driver aggression) was defined to represent the driver tendency in quantitative manner. An engine on/off control algorithm was proposed to reduce the frequent engine on/off and to maintain the battery SOC for wild driver. It was found from the simulation results that the fuel economy of the wild driver group was improved by 14.7% on average compared with that of no control.

Acknowledgments

This work was supported by The Ministry of Trade, Industry and Energy and Korea Automotive Technology Institute.

References


Authors

Seulgi Lee received B.S. and M.S. degree in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2013 and 2015. His research interests include the powertrain system, control strategy of electric vehicles, hybrid electric vehicles and plug-in hybrid electric vehicles. Since 2015, he has worked as an engineer in Hyundai Motor Company.

Jingyu Choi received the B.S. degree in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2012. He is studying as the M.S. degree student at Sungkyunkwan University. His research interests include the control of the powertrain system for PHEV, and HMT

Sunyoung Park received B.S. degree in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2014, where she has been working toward the M.S. degree. Her research interests include the powertrain system, control strategy of electric vehicles, hybrid electric vehicles and plug-in hybrid electric vehicles.

Jaemyoung Pi received B.S. in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2014, where he has been working toward the M.S. degree. He is interested in the design and control of hybrid electric vehicle.

Heejin Shin received B.S. and M.S. degree in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2013 and 2015. Her research interests include the modeling, design, and embedded systems for electric vehicles and hybrid electric vehicles. Since 2015, she has worked as an engineer in Hyundai Motor Company.

Kiyun Jeong is a senior researcher in Intelligent Control System Research Center of Korea Automotive Technology Institute. His main research interests include real car experiments, component experiments and performance evaluation of vehicle and component.
Hyunsoo Kim received a Ph.D. degree in mechanical engineering from the University of Texas at Austin, Texas, USA, in 1986. Since 1986, he has worked as a Professor at Sungkyunkwan University. His main research interests include Hybrid Electric Vehicle (HEV) transmission system design, regenerative braking, and optimal power-distribution algorithms for HEV and vehicle stability control for HEV and In-wheel Electric Vehicles.