EVS27
Barcelona, Spain, November 17-20, 2013

Analysis of Fuel Economy and Battery Life depending on the Types of HEV using Dynamic Programming

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Abstract

Increasing demands of eco-friendly vehicles, various types of hybrid electric vehicle (HEV) have been researched and released. Recently, some research has interest in not only the efficiency of the vehicle but also the durability of battery because the life of battery has influence on the cost of maintenance, stability and performance of the vehicle. In this study, backward simulation based on dynamic programming depending on the type of HEV which is consists of engine and battery or engine, battery and ultra-capacitor was conducted. The developed backward simulation algorithm can calculate the optimal fuel economy according to the driving cycle and other vehicle and components conditions. For the analysis of battery life, a battery capacity fade model was applied to the result of backward simulation. Battery life was estimated with an assumption that the vehicle drives repeatedly to follow the result of backward simulation derived to find the optimal fuel economy. From the simulation results, it is shown that HEV with ultra-capacitor has better fuel economy though it is almost similar with HEV without ultra-capacitor. However, the battery life of HEV with ultra-capacitor was estimated better because of the difference of battery power usage. Consequently, applying the ultra-capacitor to the typical parallel HEV has no large advantage in terms of fuel economy but has significant benefit in terms of battery life.

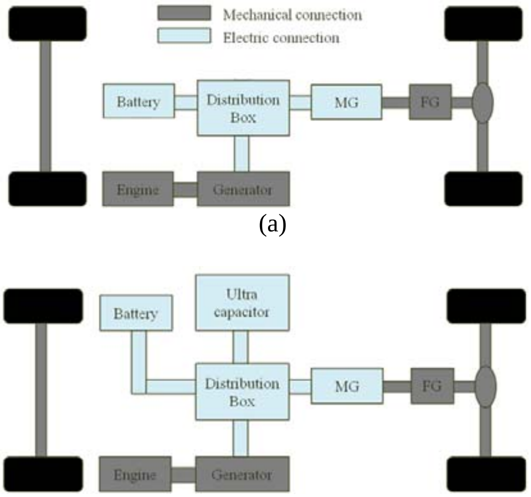
Keywords: HEV, Simulation, Optimization, Dynamic programming, Fuel economy, Battery capacity fade

1 Introduction

Increasing of demands to the fuel-saving and environmental friendly vehicles, many types of hybrid electric vehicle (HEV) have been developed [1]. Many of researchers also have been developed various optimization strategies of HEV such as, dynamic programming [2], equivalent consumption minimization strategy [3] and Pontryagin's minimum principle [4] because the strategy to distribute the output power from many power sources is important to operate the vehicle efficiently. However, it is not often considered that the characteristic of battery which has capacity fade from the use of long period though many of researches including estimation of battery life, capacity fade, have been conducted [5]. In this study, the optimization of engine-battery series HEV and engine-battery-ultracapacitor series HEV were conducted based on the dynamic programming (DP) [6]. In addition to the optimization, analysis of battery life was conducted based on the results of the optimization and capacity fade model of the battery [7]. Based on the results, the effect of the ultra-capacitor to the fuel economy and battery life was analysed.

2 System configuration of HEV

For the comparison of fuel economy and battery life, two types of vehicle were applied as in Fig. 1. Every specification of the vehicle components is the same except ultra-capacitor as in Table 1.



(a)

(b)

Figure1: System configuration of HEV: (a) engine-battery HEV, (b) engine-battery-ultra capacitor HEV

Table1: Specifications of the vehicle

Vehicle specifications and the components	
Weight	5000 kg
Tire radius	0.45 m
Frontal area	3.25 m^2
Engine	2500 cc (90kW)
Ultra capacitor	0.6 Ah
Frontal final gear efficiency	95%
Rolling resistance coefficient	0.015
Air drag coefficient	0.6
Battery	28 Ah

3 Optimization of the power sources

3.1 Dynamic programming

Dynamic programming (DP), one of global optimization theories, is based on the Bellman's principle of optimality. By the theory, DP searches every possible trajectory which can be the optimum solutions of the problem. As in Equation (1), it is possible to find optimal solution from *k* to *N* only with searching the optimal cost of *k* to *k*+1 if the solution of *k*+1 to *N* is known [8].

$$J^{*}_{k,N}(x(k)) = \min\left\{L(x(k),u(k)) + J^{*}_{k+1,N}(x(k+1))\right\} \quad (1)$$

In HEV system, the total cost of the problem, *J*, is usually defined fuel consumption of the engine. The state variable, *x*, is defined the SOC of battery or ultra-capacitor. Lastly, the control variable, *u*, is defined the output power of battery or ultra-capacitor. Because DP searches every possible trajectory, the solution from this theory is the global optimal result. Based on DP, the backward simulation program was developed as in Fig. 2. It can calculate the optimal fuel economy of not only engine-battery HEV but also engine-battery-ultra capacitor HEV. It is also possible to show that the output power of power sources including operating points of the engine, SOC of the battery and ultra-capacitor.

3.2 Backward simulation

For the simulation well-known driving cycle, FTP 72 as in Fig. 3, was applied. The results of fuel economy from the backward simulation are as in Table 2. The fuel economy of the engine-battery HEV (HEV1) has relatively low result than the result of engine-battery-ultra capacitor HEV (HEV2). However, the difference of fuel economy from two HEVs is small so that it is considered that the effect of ultra-capacitor in terms of fuel economy is not efficient. The difference between two types of HEV can be seen in Fig. 4 which is the graph of the output power of battery during

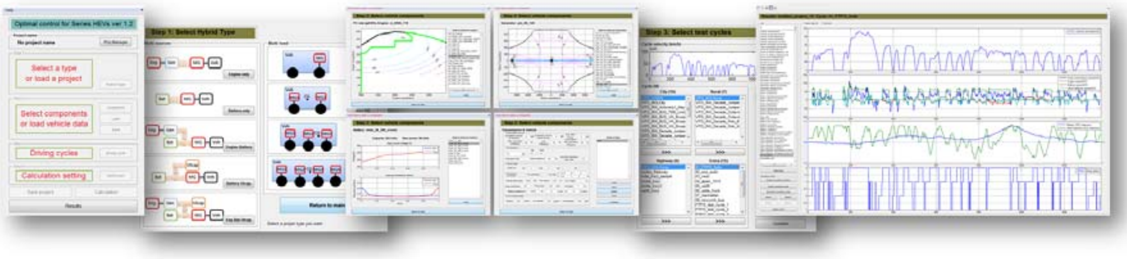


Figure2: Backward simulation program based on dynamic programming for various types of HEV

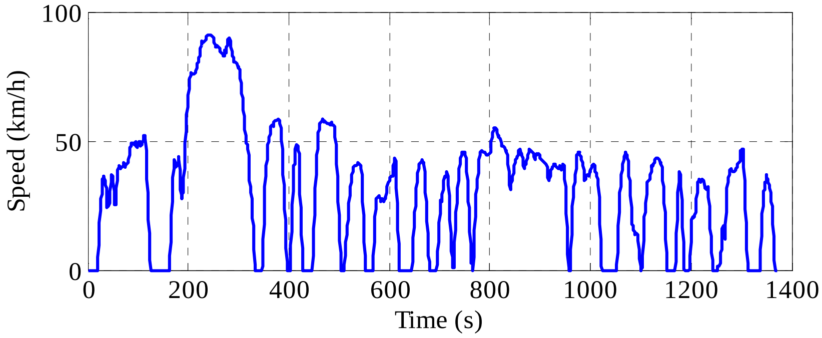


Figure3: Driving cycle of 'FTP 72'

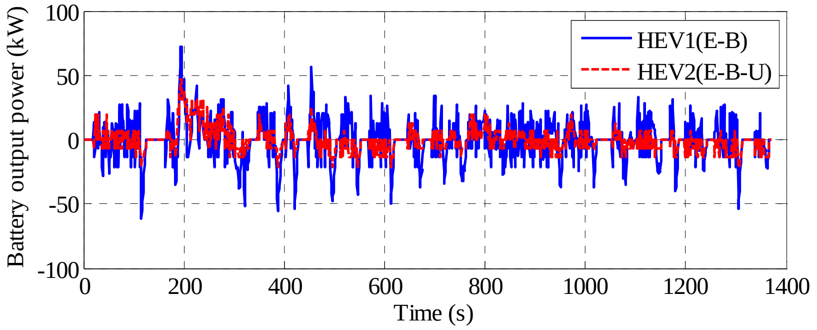


Figure4: Results of the battery output power from the simulation during FTP 72

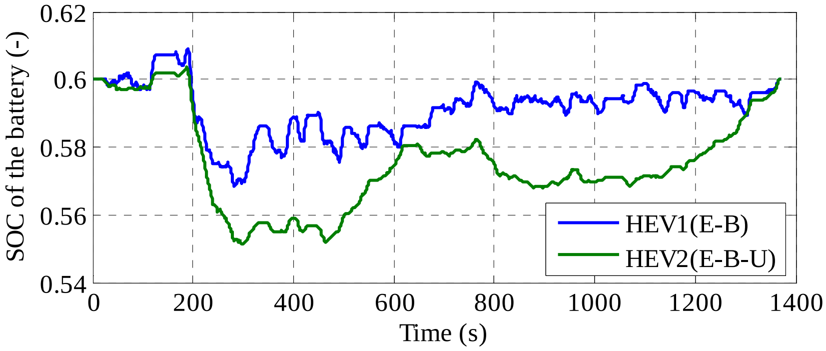


Figure5: Results of the battery SOC state from the simulation during FTP 72

simulation. In HEV with ultra-capacitor, the output power of the battery is relatively smaller than the HEV without ultra-capacitor. Extensive use of the battery is also seen in the graph of battery SOC as in Fig. 5. It is considered that HEV1 has more frequent change of discharging and charging and large gradient of SOC than HEV2. To calculate the effect of this, the battery capacity fade model was applied.

Table2: Simulation results of HEV1 and HEV2 from backward simulation

	HEV1 (E-B)	HEV2 (E-B-U)
Fuel economy (km/L)	8.99	9.38
Total output battery energy per 10 cycles (kWh)	20.57	10.26

4 Analysis of battery life

In HEV, battery life is an important issue because the battery is the important component in terms of not only fuel saving but also its expensive cost. It is known that the capacity of battery decrease as using the battery for a long period. However, there are many factors to choose quantity of the battery capacity fade. In this study, percentage of battery capacity fade is estimated according to the relation of battery life and discharging c-rate. The relation of battery life and discharging c-rate was applied according to Ning *et. al.* [7] so that it is assumed that the applied battery model to the simulation follows the characteristics of Ning *et. al.* [7] In the simulation results, the discharging energy from the battery not considering charging can be calculated as in Table 2. When the assumptions, that the

calculated whole discharging energy is outputted constantly and the ten repetition of driving cycles are one cycle of the battery experiment, were applied, the discharging c-rate of each simulation can be calculated as in Table 3. According to the battery capacity fade model the percentage of battery capacity fade depending on the system are on the Table 3. Because the variation of output battery power of HEV1 is relatively bigger than HEV2, the assumed c-rate of HEV1 is bigger than HEV2 so that the capacity fade of HEV1 is also bigger than HEV2 as in Table 3. It is considered that each capacity of the battery decreases about 14.04% and 9.91% during 35970km driving distance from 3000 repetition of driving cycle.
Referencing sources in the paper shall be done with sequential numerical references, between square brackets.

Table3: Analysis of the battery life of HEV1 and HEV2 based on the battery capacity fade model

	HEV1 (E-B)	HEV2 (E-B-U)
Assumed C-rate (Ah)	2.23	1.11
Capacity fade after 3000 cycles (%)	14.04	9.91

5 Conclusion

Backward simulation based on dynamic programming was done for the engine-battery HEV (HEV1) and engine-battery-ultracapacitor HEV (HEV2). Because of the existence of the ultra-capacitor the fuel economy of HEV2 is better than HEV1. However, the improvement of fuel economy is small considering the cost of ultra-capacitor. In terms of usage of the battery, the battery in HEV2 is less utilized than the battery of HEV1. To compare the effect of ultra-capacitor to the battery life, battery capacity fade model was applied which shows the relation between capacity fade and discharge rate of experiment. Based on the simulation result and battery model, the capacity fade of the battery in HEV1 is estimated 14.04% after 35970km of total vehicle driving distance and it is bigger than the result of HEV2 which is estimated 9.91%. Using this method, it is possible to calculate the fuel economy and battery life simultaneously though for the precise analysis the improvement of the battery capacity fade model is needed.

Acknowledgments

This work was supported by the Industrial Strategic Technology Development Program (10033126) under the Ministry of Knowledge Economy, Republic of Korea and the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science, ICT & Future Planning (MSIP) (No. 2009-0083495).

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