

Comparative Analysis of Power Characteristics for Volt PHEV Considering Drivetrain Losses

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Summary

Power characteristics of Volt 1 and Volt 2 were investigated. Using the network analysis, the system efficiency and electrical power ratio were analyzed considering the drivetrain loss. To investigate the maximum fuel economy potential, a backward simulator was developed based on dynamic programming including the drivetrain loss and power electronics loss. Using the backward simulator, mode shift map was obtained. It was found that the mode shift map by dynamic programming agreed well with the existing map and operation of the power split modes was performed in accordance with the network analysis results. In addition, vehicle performance of Volt 1 and Volt 2 were compared. It was found that the improvement of the powertrain and engine efficiency of Volt 2 in the charge sustaining mode can be achieved by application of two power split (input and compound) modes and parallel(fixed ratio extended range) mode in spite of the increased drivetrain loss.

Keywords: PHEV, network analysis, power split, drivetrain loss, dynamic programming

1. Introduction

In plug-in hybrid electric vehicle (PHEV), various powertrain configurations can be constructed by combination of MG1, MG2, engine, planetary gear, clutch and brake. Accordingly, the driving mode that can be implemented varies depending on its configuration. PHEV is driven in charge sustaining mode using the driving mode such as EV, power split, parallel or series mode meanwhile it uses mostly EV mode in charge depleting mode. In general, it is expected that the vehicle performance and fuel economy can be improved as the number of driving mode increases. However, as the number of driving mode increases, the complexity of the powertrain configuration increases, which causes the increasing cost and parasitic losses due to the increased components. Toyota Prius implements EV and power split mode using two motor/generators, one planetary gear without clutch and brake[1]. Honda i-MMD realizes EV, parallel and series mode using one clutch, but cannot implement the power split mode[2].

In GM Volt 2, five driving modes: one motor EV, two motor EV, low extended range, fixed ratio extended range and high extended range mode are implemented compared with four modes (EV#1, EV#2, power split and series) of Volt 1. To implement the additional modes, Volt 2 utilized one more planetary gear set and one-way clutch compared with Volt 1. The additional drivetrain elements cause parasitic loss, which deteriorates the fuel economy. Therefore, the positive effect by the additional modes and negative effect by the drivetrain element losses need to be evaluated for development of a new PHEV.

In the previous work, power transmission characteristics of Volt 1 and Volt 2 were investigated[3]. Using network analysis, the system efficiency of each driving mode was compared without consideration of the drivetrain component losses.

In this study, power characteristics of Volt 1 and Volt 2 were investigated considering the drivetrain losses such as planetary gear, one-way clutch, etc. and the effects the drivetrain loss and additional modes on the system efficiency were evaluated through the backward simulator based on dynamic programming.

2. System efficiency of power split mode by network analysis

When the target PHEVs, Volt 1 and Volt 2 drive in the charge sustaining(CS) mode, they select the appropriate driving mode for the demanded wheel torque and speed. Volt 2 has two(2) power split modes meanwhile Volt 1 has only one[3, 4]. The power split mode can improve the system efficiency by operating the engine on the minimum fuel consumption region using the electric continuously variable transmission function. On the other hand, it has drawbacks of low system efficiency when power circulation occurs at some speed range. In the power split mode, the direction and magnitude of the power are changed by the speed ratio, which causes the change of the system efficiency. To investigate the system efficiency of the target PHEVs, network analysis was performed considering the drivetrain loss.

2.1 Volt 1

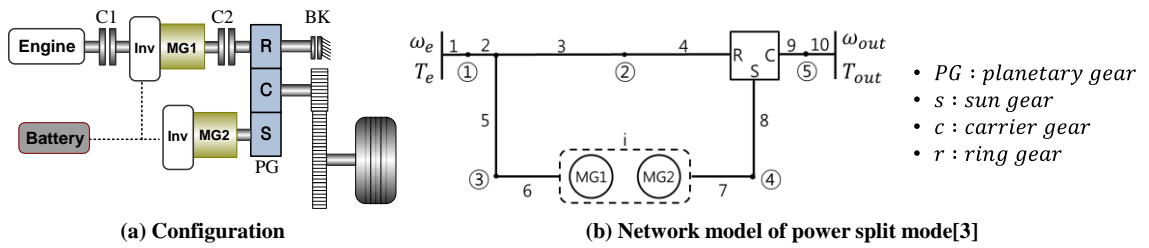


Figure1: Power split of Volt 1

Power split mode of Volt 1 has an output split type configuration. In this mode, two clutches (C1, C2) are engaged and brake (BK) is disengaged. Engine power is split at the planetary gear. MG1 and MG2 generate power or charge the battery.

In Figure1(a), network model of Volt 1 in the power split mode is shown [3]. The network model consists of the transmission elements and shafts. Number 1~9 are the torque nodes and number ①~⑤ are the speed nodes. The torque and speed relationship of each node can be expressed as follows [4],

$$[M_T] \cdot \vec{T} = \vec{\beta}_T \quad (1)$$

$$[M_\omega] \cdot \vec{\omega} = \vec{\beta}_\omega \quad (2)$$

where M_T is the torque matrix and M_ω is the speed matrix. β_T and β_ω represent the boundary torque and speed respectively.

In this study, the losses of the power electronics system(PE) and planetary gear were included. The drivetrain loss of clutch C1, C2 and brake B1 were not considered since they occurred only in the unloaded states. The PE loss was obtained from MG1 and MG2 efficiency, which was assumed to be 90%. The planetary gear loss was considered from the transmission efficiency according to the power flow as follows[5, 6],

$$\eta_{PG} = \begin{cases} 0.979 & \text{for sun-ring} \\ 1 - \frac{Z_r}{Z_r + Z_s} \cdot 0.021 & \text{for sun-carrier} \\ 1 - \frac{Z_s}{Z_r + Z_s} \cdot 0.021 & \text{for carrier-ring} \end{cases} \quad (3)$$

where η is the efficiency, Z is the number of teeth. The subscript r and s represents the ring gear and sun gear, respectively.

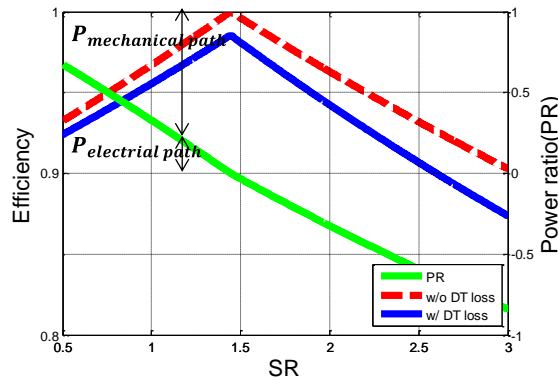


Figure2: System efficiency of power split mode

In Figure2, the system efficiency and power ratio of Volt 1 by the network analysis are shown with respect to the speed ratio. The speed ratio(SR) and power ration(PR) are defined as,

$$SR = \frac{\omega_{eng}}{\omega_{output}} \quad (4)$$

$$PR = \frac{P_{electric path}}{P_{engine}} \quad (5)$$

It is seen from Figure2 that the system efficiency decreased at low speed ($SR > 1.45$) as SR increased, in other words, the vehicle speed decreased. For $SR > 1.45$, the power ratio (PR) showed negative value, which implies that the power circulation occurred because MG1 conducted motoring and MG2 carried out generating. This energy conversion process, electrical-mechanical-electrical transmission caused the energy loss, which resulted in the decreased system efficiency. At $SR = 1.45$, all the engine power flows through the mechanical path. This speed ratio is called mechanical point (MP). At MP, the system efficiency shows 100% when the drivetrain loss is not considered. When the drivetrain loss is considered, the system efficiency decreases and it is seen that the amount of the efficiency drop increased with the increasing SR (decreasing vehicle speed). When the power circulation occurred, proportion of the split power to the mechanical path increased with SR, so magnitude of the efficiency drop became larger.

From Figure2, it is seen that the power split mode needs to be used for mid to high vehicle speed where the system efficiency is relatively high.

2.2 Volt 2

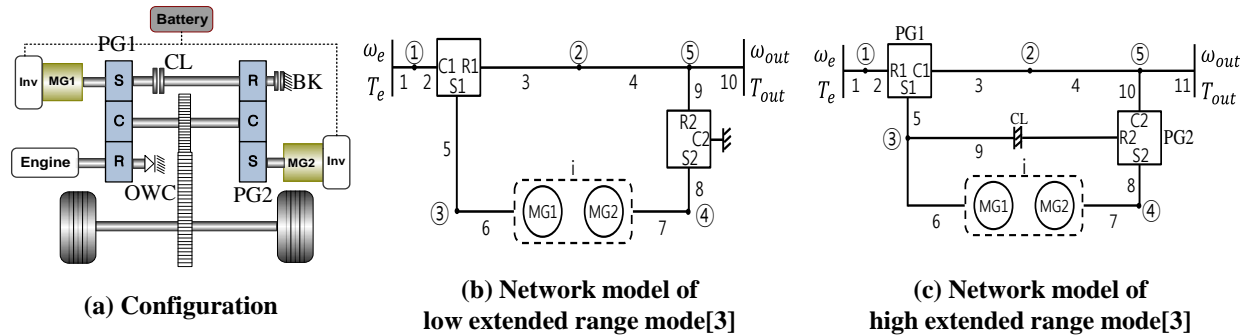


Figure3: Power split of Volt 2

Volt 2 has two power split modes: low extended range mode and high extended range mode. In the low extended range mode, brake (BK) is engaged and clutch (CL) is disengaged, which forms an input split type. In this mode, the power is split at the first planetary gear (PG1) to the mechanical path (driveshaft) and electrical path. In the high extended range mode, the clutch (CL) is engaged and brake (BK) is disengaged. In this mode, the engine power splits twice at PG1 and PG2 again.

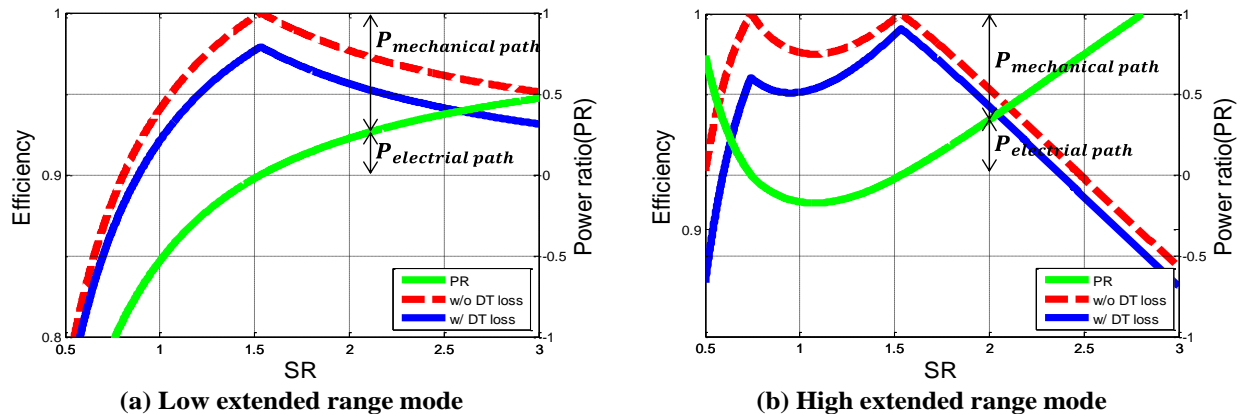


Figure4: System efficiency

Figure4 (a) illustrates the system efficiency for the low extended range mode. MP was obtained at $SR=1.535$ where PR was zero. The power circulation occurred for $SR < MP$, which caused relatively low system efficiency. It is noted that the low extended range mode plays like an input split type which can be seen in Toyota Prius. In Figure4 (b), the system efficiency and power ratio for the high extended range mode are shown. There are two MPs because the power is split twice in the planetary gear at $SR=1.535$ and $SR=0.744$, respectively. From Figure4 (b), it is seen that the system efficiency can be maintained higher when it is operated between two MPs ($0.744 < SR < 1.535$). When the drivetrain loss is considered, the system efficiency decreases and it is seen that the efficiency drop increased with the decreasing SR (increasing vehicle speed). When the power circulation occurred, proportion of the split power to the mechanical path increased with the decreasing SR, so magnitude of efficiency drop became larger.

3. Mode shift map by dynamic programming

3.1 Development of backward simulator

Backward simulator was developed based on dynamic programming (DP) considering the drivetrain loss

and PE loss in order to obtain the mode shift map. The mode shift map was obtained by solving the optimization problem using the backward simulator. In DP, the optimal driving mode, engine torque and speed, MG1/MG2 torque and speed were obtained, which provided the minimum fuel consumption for the demanded wheel torque and vehicle speed. The backward simulation process consists of local optimization and global optimization [7]. In the local optimization, minimum fuel rate is obtained with respect to the specific battery power as follows:

$$\dot{m}_{fc} = L(\omega_{eng}^*, T_{eng}^*) = g(P_{batt}) \quad (6)$$

where \dot{m}_{fc} is the fuel rate, ω_{eng}^* , T_{eng}^* are the admissible engine speed and torque and P_{batt} is the battery power.

Through the global optimization, the minimum fuel consumption is obtained for the whole driving cycle. The recursive equation and constraint are represented as,

$$\begin{aligned} \text{Recursive equation : } J_k^*(x_k) &= FC_k^* = \{g_{k-1}(P_b(k-1)) + J_{k-1}^*(SOC(k-1))\} \\ \text{Constraint : } SOC_{initial} - SOC_{final} &= 0 \end{aligned} \quad (7)$$

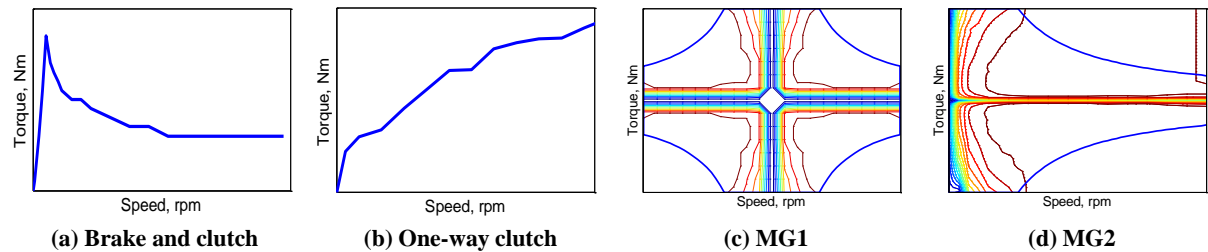


Figure5: Drivetrain loss and motor efficiency map

In the backward simulator, the drivetrain loss and PE loss were included. For the drivetrain loss, loss models of the gear, brake and clutch, one-way clutch(OWC) were considered based on the experimental results and mathematical equations [7]. For the planetary gear loss, Eq.(3) was used. In addition, for the PE loss, efficiency map of MG1 and MG2 was applied. Figure5 shows the test data used in the loss model.

3.2 Mode shift map by dynamic programming

3.1.1 Mode shift map of Volt 1

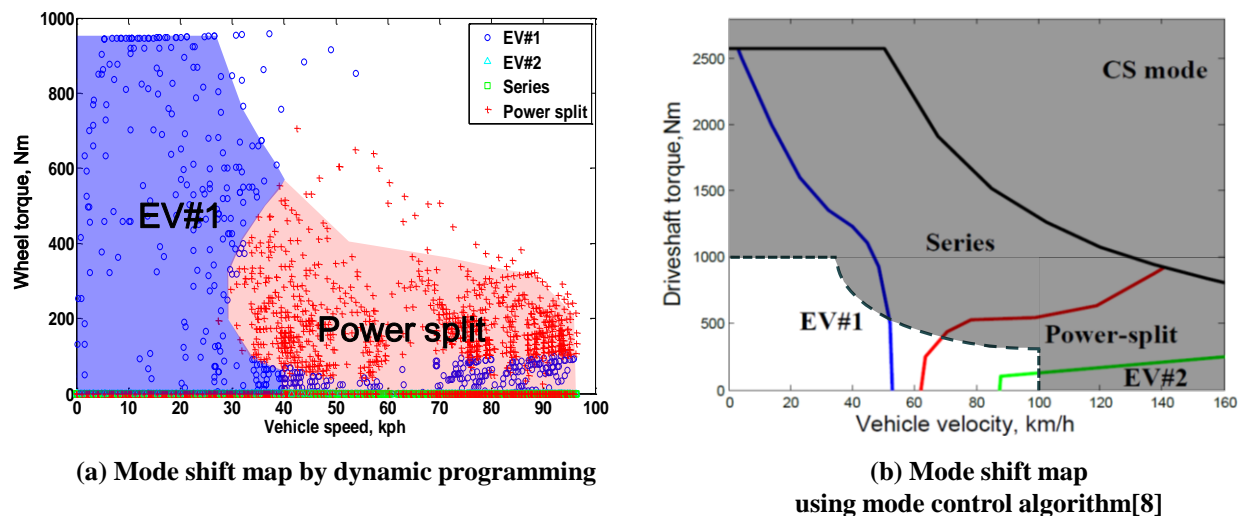


Figure6: Mode shift map of Volt 1

Using the dynamic programming (DP), a mode shift map was obtained by considering the drivetrain loss when the target PHEV drives in CS mode. In DP, the driving mode which provides the minimum fuel consumption was selected through the optimization process with respect to the demanded wheel torque and vehicle speed. In Figure6, a mode shift map (a) from the dynamic programming was compared with mode control algorithm (b) in the literature [8]. Since DP was performed for UDDS and HWFET cycle, the mode shift map by DP was obtained only for the wheel torque (0- 1000Nm) and vehicle speed (0-97 kph) available for both cycles. From the mode shift map, it is seen that the EV#1 mode was selected at low speed and high torque region meanwhile the power split mode was selected at mid to high speed region. It is noted that the speed range of the power split mode agreed with the network analysis results of the output split type in Figure2. It is found from Figure6 (a) that the series mode and the EV#2 mode were not selected due to their low efficiency. However, it is seen from Figure6(b) that the series mode was used in the speed range of more than 90 kph, which seldom appears in UDDS and HWFET. In addition, the series mode was selected in mid- to high speed with relatively large torque region in Figure6(b).

3.1.2 Mode shift map of Volt 2

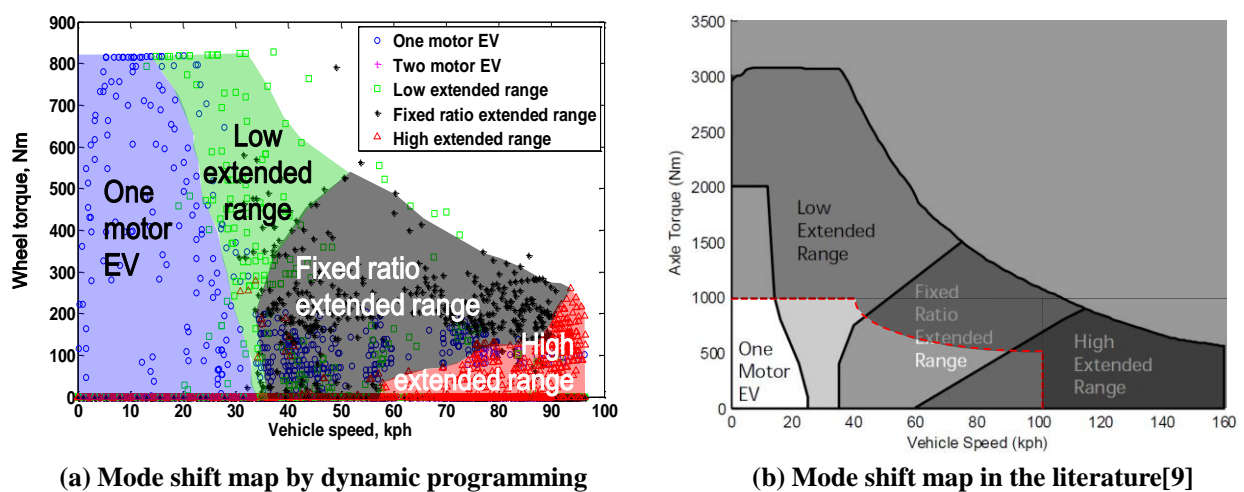


Figure7: Mode shift map of Volt 2

In Figure7 (a), mode shift map of Volt 2 is shown. As observed in the network analysis results(Figure4a, Figure4b), the low extended range mode was selected at low speed meanwhile the fixed ratio extended and the high extended range mode were used at mid and mid-to-high speed range, respectively. It is noted that the two motor EV mode was not used because its efficiency is lower than that of the one motor EV mode. It is seen that the mode shift map by dynamic programming is almost similar with the dotted region of the published results Figure7(b)[9].

4. Comparative analysis of Volt 1 and Volt 2

4.1 City cycle (UDDS)

In Table1, vehicle performance of Volt 1 and Volt 2 are compared for city (UDDS) cycle. When the drivetrain(DT) loss is considered, the fuel economy decreases as shown in Table1. The reason why the fuel economy drop of Volt 2 is larger than that of Volt 1 is that Volt 2 has relatively complicated drivetrain structure using two planetary gear and one-way clutch, which causes the increased drivetrain loss that accounts for 20.3% of the total system loss meanwhile the drivetrain loss of Volt 1 takes 9.9% of the total system loss. In Figure8, the drivetrain loss of Volt 1 and Volt 2 are compared. In Volt 1, the magnitude of the drivetrain loss appears in the order of gear (including final reduction gear), planetary gear, brake and clutch, etc. for both driving cycles. This is because the power always flows through the gear meanwhile the brake and clutch loss occur only when they do not work. In Volt 2, the drivetrain loss occurred in the order of the planetary gear, gear, one-way clutch and etc. Since two planetary gear sets are used, the planetary

gear loss takes the largest portion. The OWC loss occurs whenever the engine works. The total drivetrain loss of Volt 2 was obtained as 229.1kJ, which is larger than that of Volt 1, 134.1kJ because the number of the drivetrain components were increased to implement five driving modes.

Table1: Fuel economy, efficiency and losses of Volt 1 and Volt 2 for UDDS

UDDS		Volt 1	Volt 2
Fuel economy [km/L]	without DT loss	26.20	31.86
	with DT loss	25.37(3.2%↓)	29.65(6.9%↓)
Powertrain efficiency[%]		82.4	82.6
Engine efficiency[%]		34.0	36.0
① Engine energy[kJ]		5023.1	4549.9
② Consumed fuel energy[kJ]		14786.9	12652.5
③ Battery energy[kJ]		1966.7	1940.5
④ Wheel demanded energy[kJ]		5629.8	5361.4
⑤ Total loss[kJ](⑥+ ⑦)		1359.2(100%)	1127.2(100%)
⑥ PE loss[kJ]		1225.1(90.1%)	898.1(79.7%)
⑦ DT loss[kJ]		134.1(9.9%)	229.1(20.3%)

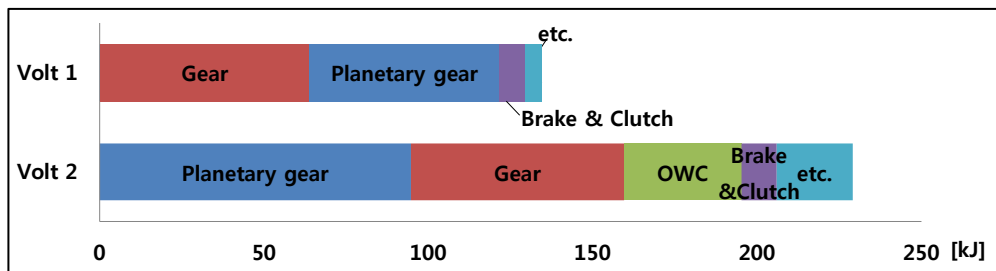


Figure8: Drivetrain loss for UDDS

On the other hand, it is noted that the PE loss of Volt 2(898.1KJ) is smaller than that of Volt 1(1225.1KJ). This is because the portion of the electric energy through PE is smaller. This can be seen in the time response of the target PHEVs in Figure9. In Figure9, the vehicle speed(a), driving mode(b), mechanical power(c), electrical power(d), drivetrain loss(e) and PE loss(f) are compared for $t=340\sim 380$ sec of UDDS. In Figure9(b), each driving mode is represented by the number as follows: for Volt 1, 1 : EV#1, 2 : EV#2, 4 : Series, 5 : power split, 6 : regenerative braking and for Volt 2, 1 : one motor EV, 2: two motor EV, 3 : low extended range, 4 : fixed ratio extended range, 5 : high extended range, 6: regenerative braking mode. It is seen that Volt 2 drives mostly using the fixed ratio extended range mode(number4) and low extended range mode (number 3) while Volt 1 drives using the power split mode(number 5). As shown in the region A in Figure9, when Volt 2 drives in the fixed ratio extended range mode(parallel mode), the magnitude of the mechanical power is larger than Volt 1(Figure9c). Accordingly, the magnitude of the electrical power (d) becomes smaller, which resulted in smaller PE loss (f).

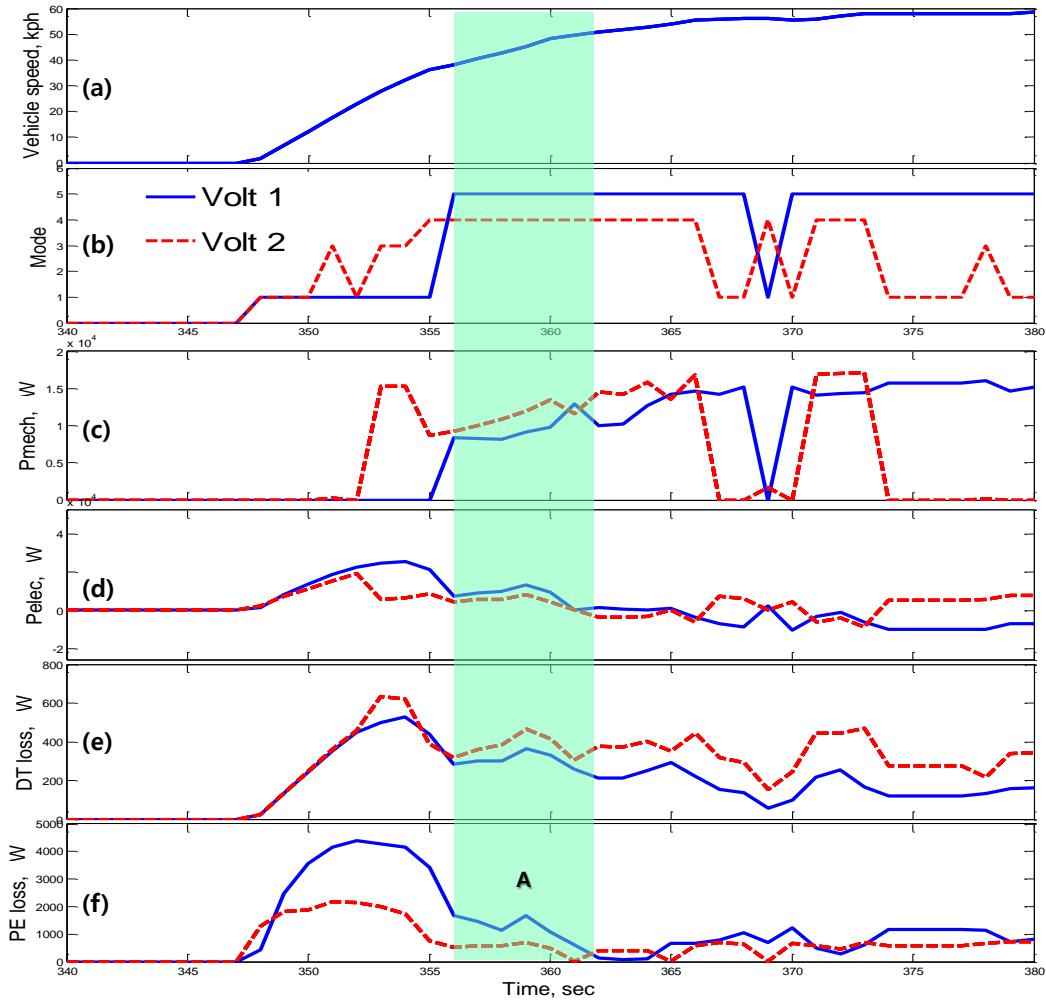


Figure9: Time response of target PHEVs for UDDS

In Table1, the powertrain and engine efficiency were compared. The powertrain and engine efficiency are defined as,

$$\begin{aligned}
 & \text{powertrain efficiency} \\
 &= \frac{\textcircled{4}}{\textcircled{1} + \textcircled{3}} \cdot \frac{\text{time for discharging}}{\text{total time}} + \frac{\textcircled{3} + \textcircled{4}}{\textcircled{1}} \cdot \frac{\text{time for charging}}{\text{total time}} \quad (8)
 \end{aligned}$$

$$\text{Engine efficiency} = \frac{\textcircled{1}}{\textcircled{2}} \quad (9)$$

As shown in Table1, the powertrain and engine efficiency of Volt 2 are higher than those of Volt 1. This efficiency improvement resulted from different drivetrain configuration of Volt 2. In Volt 2, the input split (low extended range) and compound split (high extended range) mode were adopted instead of the output split (power split) mode in Volt 1, which provided the improved system efficiency at low and mid to high vehicle speed range as shown in the network analysis results(Figure4a, Figure4b). In addition, the series mode was abandoned since its efficiency is relatively low due to the two energy conversion process.

It is seen from the comparative analysis in Table1, Figure8 and Figure9 that the fuel economy of Volt 2 was raised by the improved powertrain and engine efficiency in spite of the increased drivetrain losses.

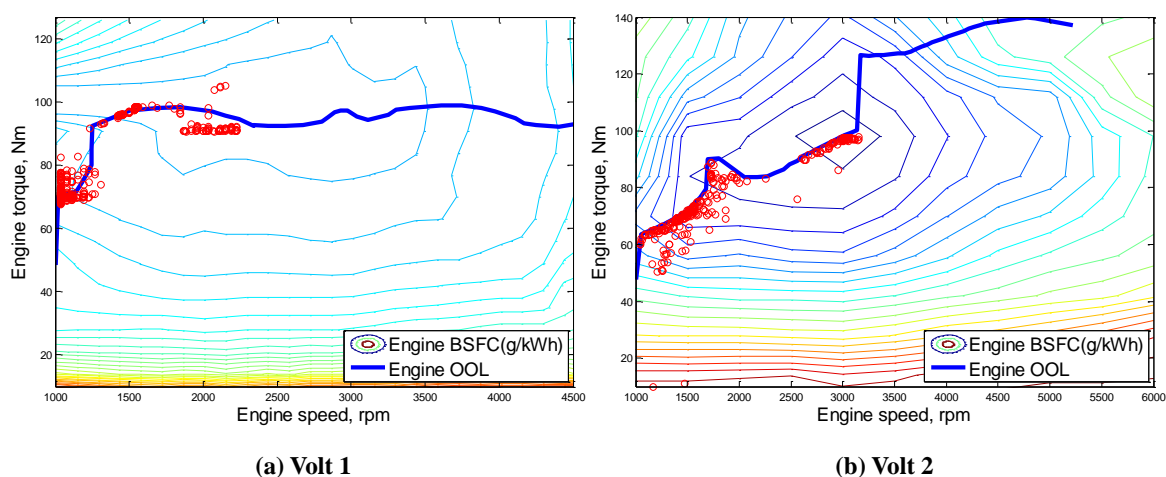


Figure10: Engine operating points for UDDS

In Figure10, the engine operating points of Volt 1 and Volt 2 are compared for UDDS. It is seen that the engine operation of Volt 2 was performed more closely on the optimal operating line (OOL) compared to that of Volt 1. This is because Volt 2 can provide more efficient engine operation using three modes: input (low extended range), compound (high extended range) and parallel (fixed ratio extended range) mode meanwhile Volt 1 has only one power split mode and the series mode when the engine is used.

4.2 Highway cycle (HWFET)

Table2: Fuel economy, efficiency and losses of Volt 1 and Volt 2 for HWFET

HWFET		Volt 1	Volt 2
Fuel economy [km/L]	without DT loss	25.32	27.76
	with DT loss	24.80(2.1%↓)	25.98(6.4%↓)
Powertrain efficiency[%]		90.4	86.6
Engine efficiency[%]		33.3	36.5
⑧ Engine energy[kJ]		6951.3	7275.8
⑨ Consumed fuel energy[kJ]		20899.1	19949.9
⑩ Battery energy[kJ]		618.6	559.5
⑪ Wheel demanded energy[kJ]		6799.2	6696.9
⑫ Total loss[kJ](⑥+ ⑦)		770.2(100%)	1132.9(100%)
⑬ PE loss[kJ]		614.2(79.7%)	715.6(63.2%)
⑭ DT loss[kJ]		155.9(20.3%)	417.3(36.8%)

In Table2, vehicle performance of Volt 1 and Volt 2 are compared for highway (HWFET) cycle. When the drivetrain (DT) loss was considered, it is seen that the fuel economy of Volt 2 was decreased by 6.4% meanwhile only 2.1 % drop was observed in Volt 1. This is because the drivetrain loss of Volt 2 (417.3KJ) is much larger than that of Volt 1(155.9 KJ). In Volt 1, the DT loss accounts for 20.3% of the total loss(Table2) and the gear loss takes for the largest part followed by the planetary gear, brake and clutch, etc.(Figure11) On the other hand, in Volt 2, planetary gear loss took the largest portion and the remaining loss appeared in order of gear and one-way clutch, etc.

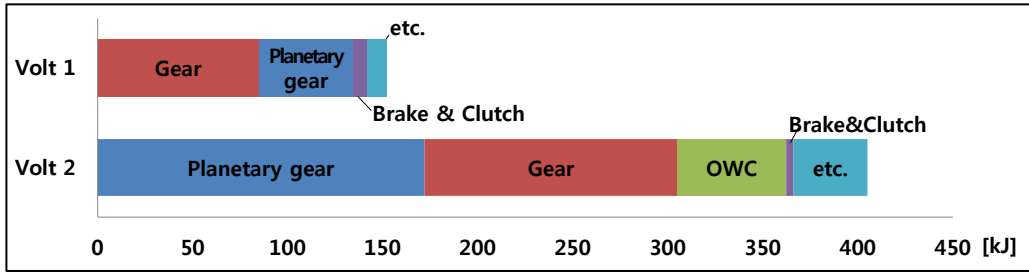


Figure11: Drivetrain loss for HWFET

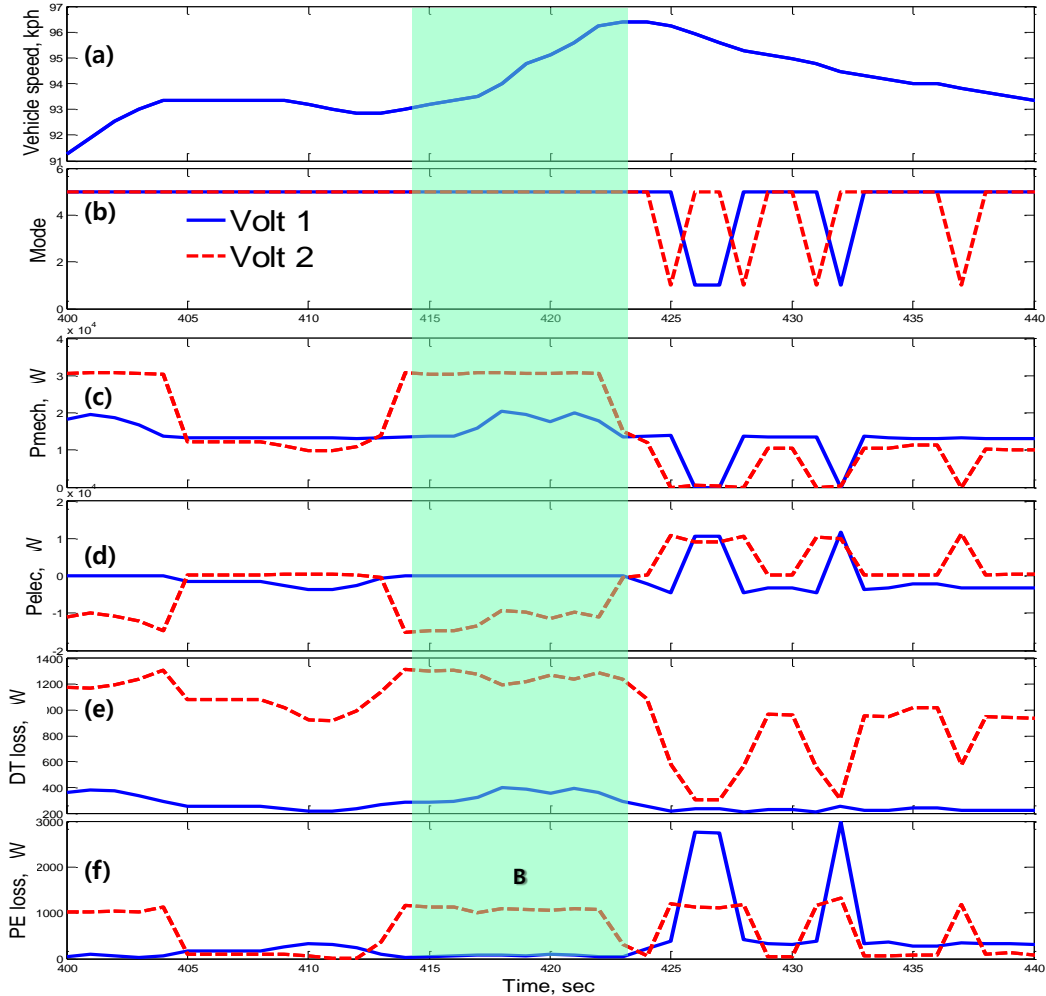


Figure12: Time response of target PHEVs for HWFET

For HWFET, the PE loss of Volt 2 is 715.6 kJ which is larger than that of Volt 1(614.2 kJ). Figure12 shows the vehicle speed(a), driving mode(b), mechanical power(c), electrical power(d), drivetrain loss(e) and PE loss(f) for $t=400\sim 440$ sec of HWFET. It is seen that Volt 1 drives mostly with number 5, the power split mode(output split type) when the vehicle speed is over 90kph meanwhile the high extended range mode(compound split type) was selected mostly for Volt 2. In the region B, the power through the mechanical path(c) of Volt 2 is larger than that of Volt 1. Therefore it causes the larger DT loss of Volt 2(e). Also, the magnitude of the electrical power of Volt 2 is around -10,000W while that of Volt 1 is almost zero. The negative power indicates that the direction of the power flow is opposite.

The increased drivetrain and PE loss resulted in the decreased the powertrain efficiency of Volt 2, 86.6% compared to Volt 1, 90.4% (Table2). However, in spite of the decreased powertrain efficiency, it is noted that the fuel economy was improved. This is because the engine efficiency was improved by operating two power split and one parallel mode meanwhile one power split and series mode were used in Volt 1. The

improved engine thermal efficiency can be seen in the engine operation trajectory in Figure13. It is seen that the engine operation of Volt 2 was performed much closer on the OOL compared to Volt 1.

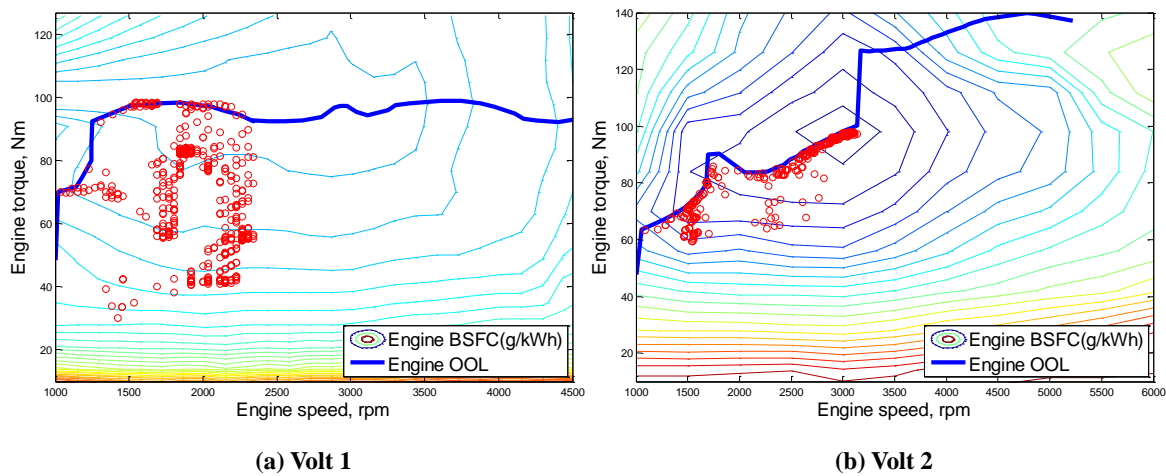


Figure13: Engine operating points for HWFET

5. Conclusion

Power characteristics of Volt 1 and Volt 2 were investigated. Using the network analysis, the system efficiency was analyzed considering the drivetrain and power electronics loss when the vehicle was operated in the power split modes. It was found from the network analysis that the PHEV system showed better efficiency near the mechanical point and the efficiency decreased when the power ratio decreased, in other words, the ratio of the electrical power increased.

To investigate the maximum fuel economy potential, a backward simulator was developed based on dynamic programming (DP). In DP, the drivetrain loss and power electronics loss were considered. Using the backward simulator, a mode shift map was obtained and compared with the existing mode shift map in the literature. It was found that the mode shift map by DP agreed well with the existing map and operation of the power split mode was performed in accordance with network analysis results.

Using the backward simulator, vehicle performance of Volt 1 and Volt 2 were compared. It was found that the improvement of the powertrain and engine efficiency of Volt 2 in the CS mode were achieved by application of two power split (input and compound) modes and parallel(fixed ratio extended range) mode in spite of the increased drivetrain losses.

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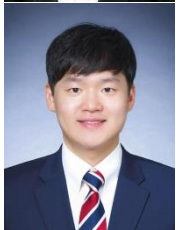
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