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Performance Analysis of PHEV depending on Electric Energy Consumption

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Summary

In this paper, the fuel consumption was evaluated according to the electric energy consumption for the power split and series-parallel type PHEV. For comparative analysis, backward simulator was developed including the losses of the power electronic and drivetrain components. In charge sustaining(CS) mode, the inferior and superior factors were obtained by analyzing the system efficiency of EV and HEV mode. It was found that the power split type showed better efficiency when the electric energy consumption was relatively low. However, as the electric energy consumption increased, the series-parallel type showed smaller fuel consumption due to the increased operation time of EV mode which has better system efficiency.

Keywords: plug-in hybrid electric vehicle(PHEV), fuel consumption(FC), electric energy consumption(EC), drivetrain(DT), power electronics(PE)

1 Introduction

PHEV(plug-in hybrid electric vehicle) is considered as a viable solution to meet CO2 regulations and fuel economy while overcoming the short travel distance of electric vehicle with moderate battery capacity.

PHEV can be designed with various configurations using the engine, motor and generator and drivetrain components. In series PHEV configuration, the engine power flows only through the electrical path meanwhile the engine and motor power flows through the mechanical and electrical path separately in parallel configuration. In power split type, the engine power is split at the power split device to the mechanical and electrical path. The power flow in PHEV varies depending on its configuration, which affects on the performance and system efficiency. Most PHEVs are designed to implement more than two(2) mode using the drivetrain components such as planetary gear, clutch and brake, etc.

In addition, the PHEV system efficiency varies depending on the power distribution ratio as well as the mode control strategy.

Previous studies were focused on the PHEV system efficiency by the power split ratio and speed ratio for the input and compound power split type[1]. Configuration analysis of the PHEV system was performed on the input power split and series-parallel type to derive the inferior and superior factor of each system for the given driving conditions[2]. And comparison of the parallel pre-transmission, series and power split type configuration was performed using backward simulator based on the dynamic programming[3].

In these works, to obtain the system efficiency, only the motor and battery efficiency were considered and the drivetrain component losses were neglected or assumed to be constant values. However, the drivetrain component losses vary depending on the magnitude and direction of the power that changes by the mode and control strategy.

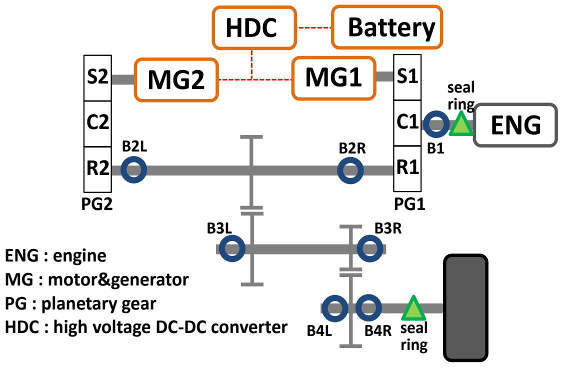
In this study, a comparative study was performed for a power split type and series-parallel type PHEV in terms of the fuel consumption and system efficiency considering the drivetrain and power electronic component losses. To investigate the performance, a backward simulator was developed for the target PHEVs and drivetrain component loss models were constructed using the mathematical governing equation and experiments. And inferior and superior factors were evaluated for the target PHEVs using backward simulation.

2 System description

For the target PHEV, power split type (Toyota Prius 3rd) and series-parallel type(Honda i-MMD) were selected.

2.1 Power split type

In Figure 1, the vehicle configuration and specifications for the power split type PHEV investigated in this study are shown. The power split type PHEV consists of an engine, a high voltage DC-DC converter(HDC), two motor-generator(MG) and two planetary gears(PG). It can provide two driving modes : EV and power split mode.



Vehicle specifications		
Engine	Max power Max torque	115 kW 190 Nm
MG1	Max power Max torque	70 kW 55 Nm
MG2	Max power Max torque	90 kW 290 Nm
Battery	Max power Capacity	60 kW 9 kWh
Vehicle	Mass Tire radius	1800 kg 0.32 m

Figure1: Vehicle configuration and specifications for power split type.

In EV mode, the power from MG2 is transmitted to the wheel through the planetary gear. During the power transmission, losses occur both in the power electronic(PE) system and in the drivetrain components. In the PE system, losses take place in MG2. The drivetrain loss occurs in the gear, planetary gear(PG), bearing, seal ring, etc. The drivetrain component loss depends on the load. Also, the drivetrain loss such as drag occurs when the drivetrain component is unloaded. In addition, unloaded loss occurs in MG1 when it is freely rotating.

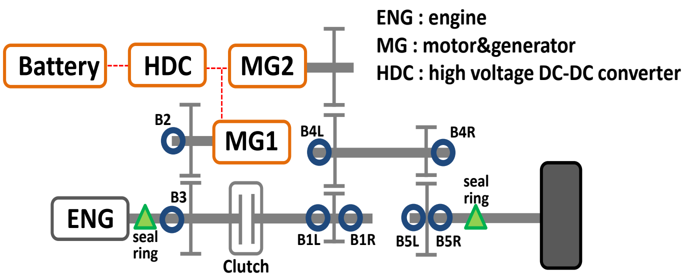
In power split mode, the engine power is split at planetary gear to the mechanical and electrical path. In this mode, losses also occur both in the PE system and in the drivetrain. Magnitude of these losses varies depending on the power flow, in other words, the torque, speed and direction that change according to the operating mode. In Table 1, the PE and drivetrain component losses are shown for EV and power split mode.

Table1: Drivetrain and PE losses of operating mode for power split type.

Operating mode		EV	Power split
Engine		Off	On
MG1		Off	On
MG2		On	On
Power electronics(PE) loss		battery, HDC, MG2	battery, HDC, MG2, MG1
Drivetrain loss	Loaded	gear, bearing, PG	gear, bearing, PG
	Unloaded	bearing, churning, MG1 unloaded, seal ring	bearing, churning, seal ring

2.2 Series-parallel type

In Figure 2, the vehicle configuration and specifications for the series-parallel type PHEV are shown. The target PHEV has three operating modes : (1) EV, (2) series and (3) parallel mode.



Vehicle specifications		
Engine	Max power Max torque	115 kW 190 Nm
MG1	Max power Max torque	118 kW 109 Nm
MG2	Max power Max torque	115 kW 325 Nm
Battery	Max power Capacity	60 kW 9 kWh
Vehicle	Mass Tire radius	1800 kg 0.32 m

Figure2: Vehicle configuration and specifications for series-parallel type.

In EV mode, the clutch is disengaged and MG2 drives the vehicle. Even though the engine and MG1 are not rotating, the drag occurs between the clutch plates. In series mode, the engine drives MG1 to generate the electric power and this power is transmitted to the wheel via MG2. In this process, the power loss occurs when the mechanical power is transformed to the electric power, and once again to the mechanical power. In parallel mode, the clutch is engaged, and the engine and MG2 drive the vehicle together. Since the clutch is engaged, no drag occurs in the clutch. Instead, the MG1 unloaded loss occurs when MG1 is freely rotating. As described above, the PE loss and drivetrain component loss vary depending on the operating mode. In Table 2, the PE and drivetrain component losses are shown for each mode.

Table2: Drivetrain and PE losses in each operating mode for series-parallel type.

Operating mode		EV	Series	Parallel
Engine		Off	On	On
MG1		Off	On	Off
MG2		On	On	On
Power electronics(PE) loss		battery, HDC, MG2	battery, HDC, MG2, MG1	battery, HDC, MG2
Drivetrain loss	Loaded	gear, bearing	gear, bearing	gear, bearing
	Unloaded	bearing, churning, clutch, seal ring	bearing, churning, clutch, seal ring	bearing, churning, MG1 unloaded, seal ring

3 Backward simulator taken into account drivetrain losses

3.1 Component loss models

The PE loss was obtained from the efficiency map of MG1, MG2 and HDC. The HDC loss was determined according to the voltage for a boost converter. The MG1 and MG2 loss were obtained from the efficiency map for each boosted voltage.

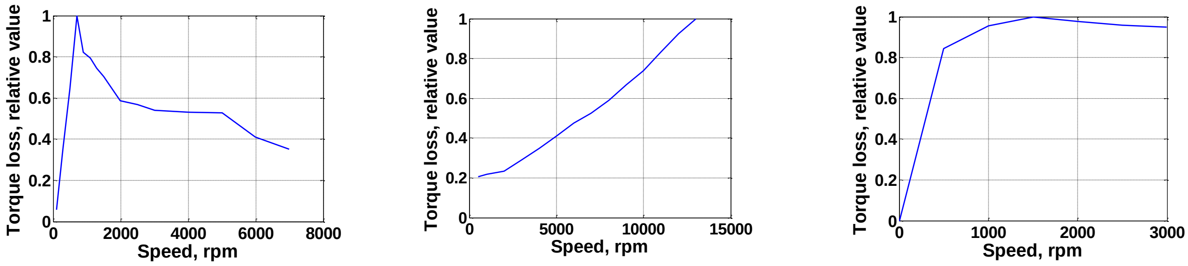
The drivetrain component losses were modeled using the mathematical governing equations and experimental results[4].

In Table 3 and Table 4, the drivetrain loss models are shown.

Table3: Mathematical governing equation for drivetrain loss models

Gear[2]	$T_{\text{loss\_Gear}} = C_{Gear} \times T_{\text{in}}$
Planetary gear(PG)[5,6]	$T_{\text{loss\_PG\_carrier}} = C_{\text{PG}} \times T_{\text{in\_PG}}$ $T_{\text{loss\_PG\_ring}} = C_{\text{PG}} \times \left(\frac{Z_r}{Z_r + Z_s}\right) \times T_{\text{in\_PG}}$ $T_{\text{loss\_PG\_sun}} = C_{\text{PG}} \times \left(\frac{Z_s}{Z_r + Z_s}\right) \times T_{\text{in\_PG}}$
Bearing	$T_{\text{loss\_BRGload}} = f_1 \times {P_1}^a \times {d_m}^b \times 10^{-3}$
Churning[7]	$T_{\text{loss\_churning}} = \frac{1}{2}\rho\omega^2 {R_p}^3 S_m C_m$

Table4: Experimental map for drivetrain loss models



<Clutch> <MG unloaded> <Seal ring>

3.2 Backward simulator based on dynamic programming

In this study, a backward simulator using dynamic programming(DP) was developed to evaluate the electric energy consumption, fuel economy and system efficiency for each PHEV system type. DP is a global optimization method based on Bellman's principle[8]. When the whole driving information is given, DP finds an optimal battery SOC trajectory to minimize the fuel consumption under the given initial and final SOC[9].

For each time step, the control variable is the battery power and the state variable is SOC. When the battery power is given, the instantaneous optimal operating points of the engine, MG1, MG2 are determined. Also, the transmitted torque, speed and losses of the drivetrain components are calculated[4].

In global horizontal plane, in other words, time-SOC plane[10], the optimal fuel consumption was calculated by adding the optimal consumption rate for each time step. And the optimal SOC trajectory which meets SOC constraints was obtained.

DP simulations were performed using the following recursive equation and constraint,

$$J_k^*(x_k) = FC^*_k = \{g_{k-1}(P_b(k-1)) + J_{k-1}^*(SOC(k-1))\} \tag{1}$$

$$SOC_{\text{initial}} - SOC_{\text{final}} = \text{constant} \tag{2}$$

where k is the discrete time stage, J_{k-1}^* is the optimal fuel consumption from start to k − 1 stage, J_k^* is the optimal fuel consumption from start to k stage, g_{k-1} is the fuel consumption rate at k − 1 stage, and FC is the fuel consumption.

4 Performance analysis depending on electric energy consumption

A performance analysis depending on the electric energy consumption(EC) was conducted for the power split type(Figure 1) and series-parallel type PHEV(Figure 2).

In CD(charge depleting) mode, both PHEVs are driven only using the electric energy. In CS mode, MG1, MG2 and the engine are used together to maintain the battery SOC. If the battery final SOC is equal to the initial SOC, the electric energy consumption(EC) becomes zero, which implies that the demanded vehicle energy is supplied by the engine. This inference tells that when the final SOC is fixed, the EC increases as the initial SOC increases. Using the DP simulator developed in this study, the engine fuel consumption(FC), the drivetrain and PE loss were investigated for various initial SOC. DP simulations were performed for various initial battery SOC(30%~45%) under urban dynamometer driving schedule(UDDS) cycle. Figure 3 shows the DP simulation results of the battery SOC trajectory with the EC per distance. Since the EC represents the information of the energy consumption for the given cycle distance including the battery depletion, it can be used as a comparative parameter to evaluate the system efficiency. It is seen that as the battery SOC increases from 30% to 45%, the EC is increased from 0Wh/km to 112.6Wh/km. As the EC increases, the operation time of EV mode increases and correspondingly, the operation time of HEV mode decreases. In addition, when the EC is high enough, the vehicle runs only using EV mode.

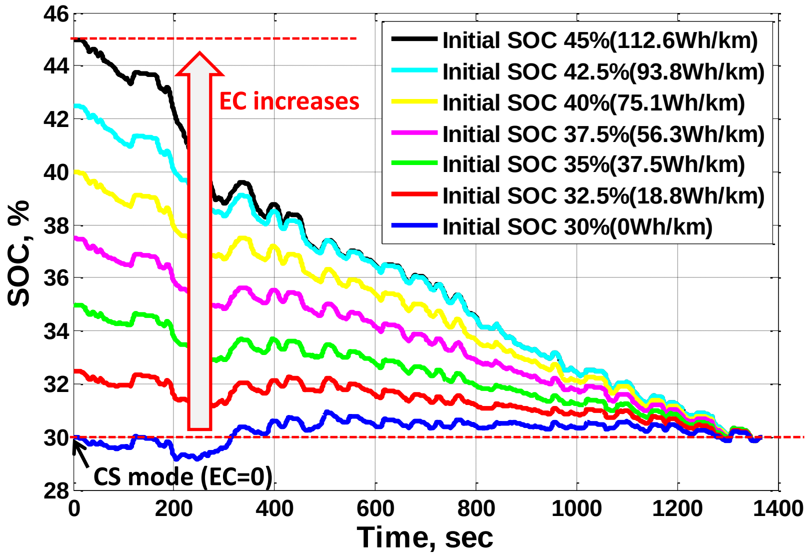


Figure3: Optimal SOC trajectories through DP simulation of power split type PHEV for various initial SOC when the final SOC is fixed(UDDS cycle).

4.1 Inferior and superior factor in each operating mode

To find the inferior and superior factor in each operating mode, the PE and drivetrain losses were compared for UDDS cycle when the target PHEV drives in CS mode. In Table 5, the average power loss of PE system and drivetrain components are compared.

In CS mode, EV and power split mode are used for the power split type PHEV meanwhile EV, series and parallel mode are used for the series-parallel type. In EV mode, the total average power of the drivetrain loss for the power split type(297.2W) is larger than that of the series-parallel PHEV(170.5W). This is because the MG1 unloaded loss(73.9W) and planetary gear loss(82.5W) occur even when they are not working, which can be pointed out as the inferior factor of the power split type.

In HEV mode, the total average power of the PE loss in series mode(6107.3W) has the largest value since the engine power to drive the vehicle is transformed to the electrical power at MG1 and again transformed to the mechanical power at MG2. This energy conversion process causes the power loss. On the contrary, in power split and parallel mode, the demanded vehicle power is supplied by the engine and MG2, and the power which flows through the electrical path is relatively small, which results in the smaller PE loss.

From Table 5, it is seen that the PE loss in series mode of the series-parallel type PHEV is the inferior factor, but relatively small drivetrain loss in EV mode becomes the superior factor compared with the power split type PHEV.

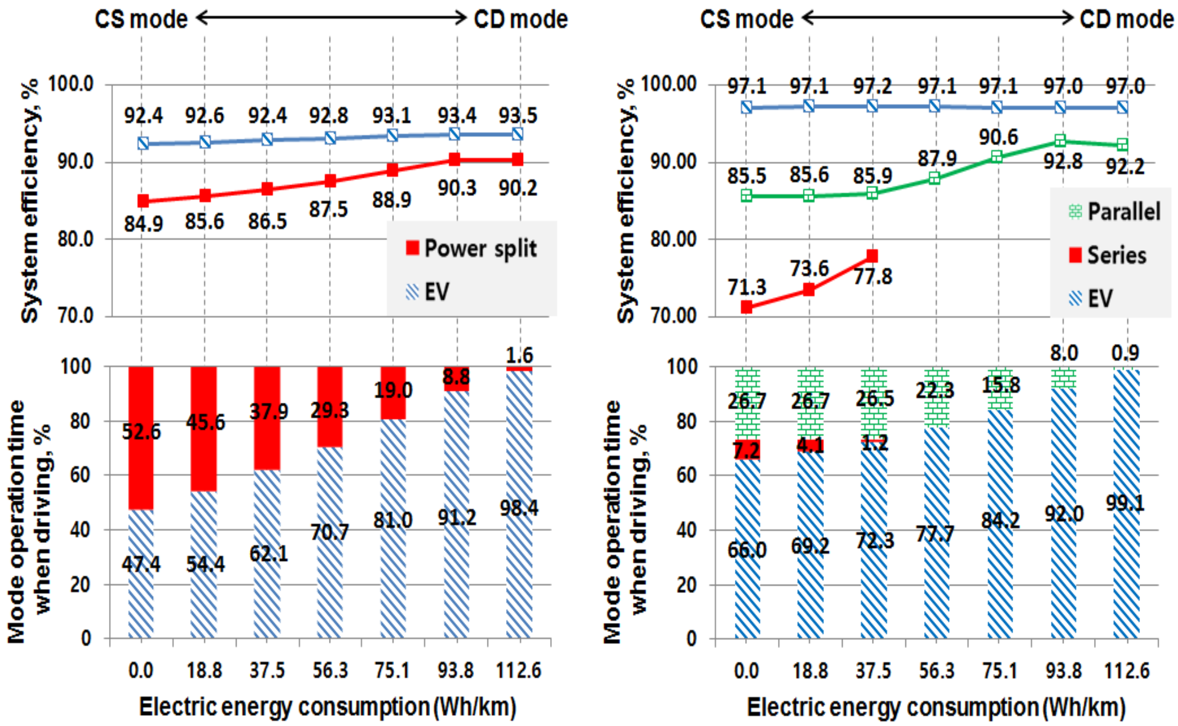
Table5: DP simulation results for CS mode.

Type		**Power split**		**Series-parallel**		
Mode		**EV**	**Power split**	**EV**	**Series**	**Parallel**
Average power loss, W	MG1	0	561.4	0	3580.0	0
	MG2	690.8	478.7	995.6	2110.9	677.8
	HDC	23.1	18.5	36.9	87.3	38.4
	Acc	329.4	329.6	329.5	329.1	329.6
	PE total	1043.6	1388.0	1361.9	6107.3	1045.3
	Gear	37.2	111.3	58.3	547.3	232.0
	Planetary	82.5	197.2	0	0	0
	Bearing	51.9	99.2	13.2	65.5	74.4
	MG1 unloaded	73.9	0	0	0	56.7
	Clutch	0	0	30.7	21.8	0
	Diff.	47.2	126.6	64.5	180.0	113.8
	Seal ring	4.4	9	3.8	9.1	14.3
	Drivetrain total	297.2	543.6	170.5	825.5	491.1

4.2 Fuel consumption depending on the electric energy consumption (EC)

To evaluate the effect of the operating mode on the fuel economy, the system efficiency and mode operation time were compared for each mode when the electric energy consumption(EC) increases.

In Figure 4a, the system efficiency and mode operation time are compared for the power split type PHEV. In CS mode when the EC is equal to 0, the operation time of EV mode is 47.4% meanwhile that of power split mode is 52.6% to charge the battery for SOC balancing even if the system efficiency of power split mode is lower than EV mode. As the EC increases, the operation time of EV mode increases.



(a) power split type (b) series-parallel type

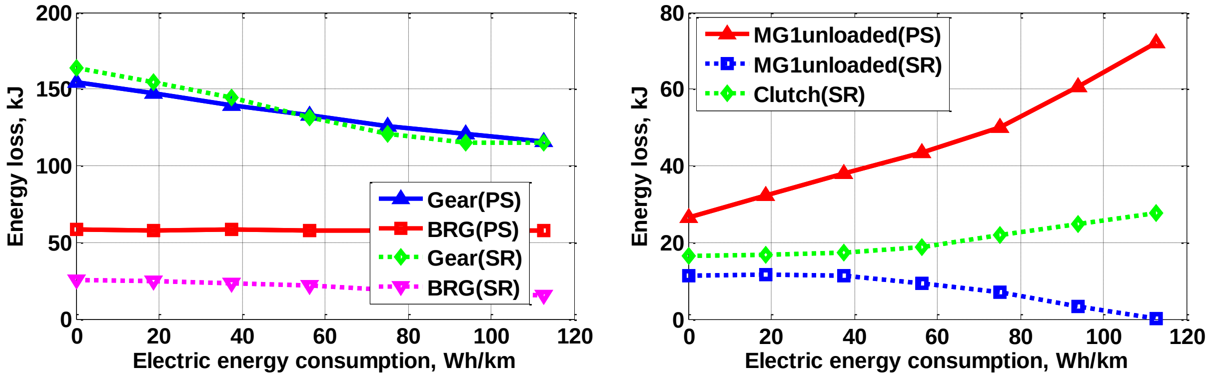
Figure4: System efficiency and operation time when driving UDDS cycle for various electric energy consumption.

Figure 4b shows the system efficiency and mode operation time for the series-parallel type PHEV. In CS mode, the operation time of EV, series and parallel mode are 66%, 7.2% and 26.7%, respectively.

In series mode, since the PE loss plays as an inferior factor, the system efficiency of series mode(71.3%) is much lower than that of parallel(85.5%) and EV(97.1%) mode. In this reason, series mode is used for SOC balancing in low EC value. When the EC is higher than 56.3Wh/km, series mode is not used because it is not necessary to charge the battery. As the EC increases, operation time of EV mode also increases, which implies that the vehicle fuel economy is mainly affected by the efficiency of EV mode.

Figure 5a shows the loaded losses of the drivetrain components for the power split type and series-parallel type with respect to the EC. Gear loss is 114~163kJ, which are similar for both system. Gear loss decreases with increasing EC. This is because the mechanical path in EV mode is relatively simple and the gear loss decreases as the operation time of EV mode increases. The bearing loss does not change much. Bearing loss of power split type(55kJ) is larger than that(15~25kJ) of series-parallel type due to the larger bearing diameter.

Figure 5b shows MG1 unloaded loss and clutch drag loss. As the EC increases, the MG1 unloaded loss of power split type increases from 26kJ to 72kJ with the increasing EC because the operation time of EV mode becomes larger. On the other hand, in the series-parallel type, the clutch is disengaged during EV mode. In this mode, MG1 is mechanically disconnected from the vehicle and MG1 does not rotate. As the operation time of EV mode becomes longer, the MG1 unloaded loss decreases(11~0kJ), and the clutch unloaded loss increases(16~27kJ).



(a) loaded losses (b) unloaded losses

Figure5: Drivetrain losses for the power split type and series-parallel type by increasing EC (UDDS cycle).

In Figure 6, the fuel consumption per distance(FC) was compared for the power split type and series-parallel type PHEV.

When the vehicle drives in CS mode, the FC of the series-parallel type is larger than that of the power split type. This is because the series-parallel type needs to be operated in series mode for the battery SOC balancing, which causes the increased PE loss. On the other hand, as the EC increases, the operation time of EV mode increases. When the operation time of EV mode increases, the efficiency of EV mode accounts for the FC. Since the system efficiency of EV mode of the series-parallel type is 97.0~97.1%, which is higher than that of the power split type, 92.4~93.5%, the FC of the series-parallel type becomes smaller than that of the power split type at EC=56.3Wh/km in Figure 6.

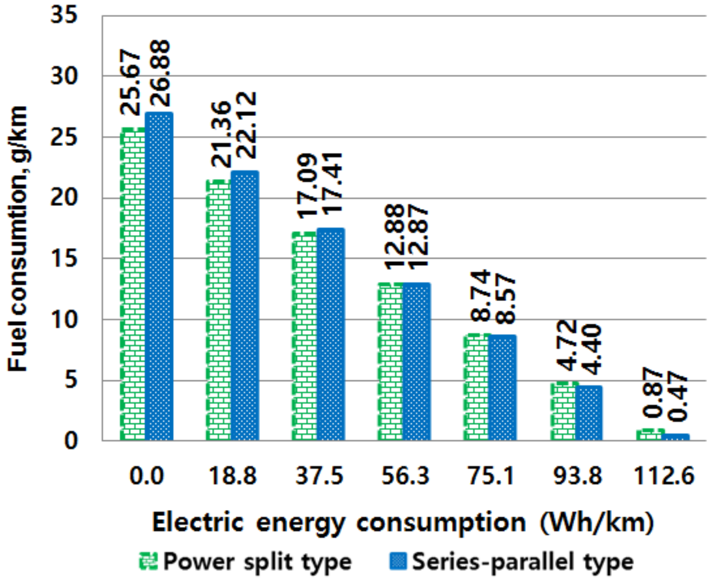


Figure6: Comparison of fuel consumption per distance for power split type and series-parallel type for various electric energy consumption.

5 Conclusion

A performance analysis was conducted depending on the electric energy consumption for the power split type and series-parallel type PHEV. To evaluate the fuel consumption, a backward simulator was developed using dynamic programming. In the backward simulator, the power electronic system loss and drivetrain components loss were considered based on the mathematical governing equation and experimental results. To obtain the inferior and superior factors in each operating mode, the system efficiency and average power loss in EV and HEV mode were compared. It was found that the power split type showed better system efficiency when the electric energy consumption is relatively low since the average power loss of HEV mode for power split type is smaller than that of the series-parallel type. However, as the electric energy consumption increased, the series-parallel type has superior characteristic due to the increased operation time of EV mode which has better system efficiency and lower drivetrain components loss. The inferior and superior factors for the power split and series-parallel type can be used in design of new PHEV configuration.

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