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Optimization of Engine Control Methods for Range Extender-Type Plug-in Hybrid Vehicles

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Abstract

This paper discusses the effects of different engine control methods on vehicle performance using a compact range extender-type PHV with a series-hybrid system. Vehicle performance was analyzed and compared in detail using two typical engine control methods: the variable control method, which drives the engine in accordance with the vehicle load, and the constant control method, which drives the engine at a constant maximum load efficiency. Specifically, by evaluating the performance in both driving tests by a test vehicle and driving simulations, we identified the characteristics of each engine control method and confirmed which is superior in terms of the seven PHV performance indices determined by the Japanese Ministry of Land Infrastructure and Transport. The comparison results quantitatively verified that the constant control reduced engine loss but caused battery loss to increase. However, since the best control method is determined by the engine and battery loss characteristics of the target vehicle, the constant control method enables superior mileage for the vehicle examined in this research due to its large engine loss reduction effect. In our case, 7.9% improvements of the charge sustaining mode mileage F_{CS} and 7.6% improvements of the combined mileage F_{PH} have been achieved by adopting the constant control method.

Keywords: control system, PHEV(plug in hybrid electric vehicle), vehicle performance

1 Introduction

Vehicle electrification is regarded as a potential means of addressing environmental and energy-related problems. The research described in this paper focuses on plug-in hybrid vehicles (PHVs), which combine characteristics from both hybrid vehicles (HVs) and pure electric vehicles (EVs). Since mass-production PHVs are relatively new in the market, it is likely that manufacturers will develop vehicles with systems that differ from existing vehicles in terms of engine control, component specifications, and the like.

Consequently, this research examined the effects of different engine control methods on vehicle performance using a compact range extender-type PHV with a series-hybrid system. Vehicle performance was analyzed and compared in detail using two typical engine control methods: the variable control method, which drives the engine in accordance with the vehicle load, and the constant control method, which drives the engine at a constant maximum load efficiency. Specifically, by evaluating the performance in both the driving test by a test vehicle and the driving simulation, we identified the characteristics of each engine control method and confirmed which is superior in terms of the seven PHV performance indices determined by the Japanese Ministry of Land Infrastructure and Transport.

2 Details of Test Vehicle and Vehicle Performance Indices

2.1 Test Vehicle

Figure1 and Table1 show the appearance and specifications of a test vehicle. The test vehicle is a PHV based on a conventional internal combustion engine vehicle. The engine displacement is 660 cc and the PHV is 218 kg (approximately 22%) heavier than the base vehicle due to the extra electrical equipments such as the motor, generator, battery, and the like.

The test vehicle uses a series-hybrid system, which is the most similar system to that adopted by pure EVs. The main feature of this type of series-hybrid system is its high control flexibility since the engine is not directly connected to the wheels. Naturally, this PHV emits zero emissions when driving in charge-depleting (CD) mode.

Figure1: Vehicle Appearance

Table1: Vehicle Specification

	Parameter	Value
Vehicle	Curb Weight	1218 kg (Base 1000 kg)
	Dimensions (L×W×H)	3755×1690×1510 mm
Battery	Nominal Voltage	266 V
	Capacity	2.66 kWh (10 Ah)

2.2 Engine Control Methods

Taking advantage of the flexible engine control of the series-hybrid system, in which the engine is not directly connected to the wheels, vehicle performance was compared and analyzed with two types of engine control: variable and constant control. Specifically, the variable control method determines the engine power primarily based on the accelerator angle. In contrast, the constant control method drives the engine at all times at the maximum efficiency point. An outline of these controls is described below.

2.2.1 Variable Control Method

Table2 lists the engine on/off conditions in CD mode and charge-sustaining (CS) mode with the variable control method. CD mode adopts all-electric (AE) control in which the engine is stopped at all times. In CS mode, the engine power is controlled in accordance with the accelerator angle.

Table2: Engine On/Off Conditions (Variable Control)

CD mode (SOC: 90-30 %)	CS mode (SOC: 30 %)	
	OFF	ON
●Engine OFF at all times	● Drive Power: 5 kW or under ● Drive Torque: 50 Nm or under ● Motor Speed 1850 rpm or under ● SOC : Over 40%	● Motor Speed: 2470 rpm or Over

2.2.2 Constant Control Method

Table3 lists the engine on/off conditions with the constant control method. In the same way as the variable control method, CD mode adopts AE control. However, in CS mode, once the engine is switched on, it operates at all times at its maximum efficiency point. The battery is charged until SOC=40%.

Table3: Engine On/Off Conditions (Constant Control)

CD mode (SOC : 90-30 %)	CS mode (SOC : 30 %)	
	OFF	ON
●Engine OFF at all times	● Vehicle Speed: 10 km/h or under ●SOC: Over 40%	● Vehicle Speed: 40 km/h or over & SOC: Under 30% ●SOC: Under 25 %

2.3 PHV Performance Indices

This research evaluated the performance of the PHV using the following seven indices [1], [2]. It should also be noted that the performance of the vehicles was only compared under hot start conditions.

1) R_{CD} (CD range (km)): The possible driving distance in CD mode

2) F_{CD} (CD mileage (km/l)): The mileage in CD mode. However, a value cannot be calculated for this index since the vehicle adopts AE control in CD mode in this research.

3) F_{CS} (CS mileage (km/l)): The mileage in CS mode

4) F_{PH} (combined mileage (km/l)): The combined mileage for F_{CD} and F_{CS}. This index is calculated as follows.

$$1/F_{PH} = UF \cdot 1/F_{CD} + (1-UF) \cdot 1/F_C \qquad (1)$$

where, the utility factor (UF) indicates the proportion of CD mode range within the total range of the vehicle. This information is derived from measured daily driving distance data for passenger vehicles in Japan. It is obtained as a function of R_{CD} using the following equation [2], [3].

$$\begin{aligned} UF(R_{CD}) = 1 - \exp(29.1 \cdot (R_{CD}/400)^6 \\ -98.9 \cdot (R_{CD}/400)^5 + 134 \cdot (R_{CD}/400)^4 \\ -89.5 \cdot (R_{CD}/400)^3 + 32.5 \cdot (R_{CD}/400)^2 \\ -11.8 \cdot (R_{CD}/400)) \end{aligned} \qquad (2)$$

5) R_{EV} (equivalent EV range (km)): The distance that the vehicle can be driven using electrical energy obtained from external charging. Since this research adopts AE control, R_{CD} and R_{EV} have the same value.

6) E_C (single charge electrical energy (kWh)): The electrical energy required to fully charge the battery using an external charger after the vehicle has finished driving.

7) E_{CR} (electrical mileage (km/kWh)): The electrical mileage that is used in CD mode. It is calculated by the following equation.

$$E_{CR} = R_{EV}/E_C \qquad (3)$$

In addition, the mileage was corrected to calculate F_{CS} based on a zero battery charge balance comparing before and after the test cycle. Figure2 plots the reciprocal of F_{CS} obtained with different initial battery SOC values before the test cycle. The mileage after the correction is derived from the intersection of the straight approximation line. The same correction calculation was performed for the energy flow amount described later.

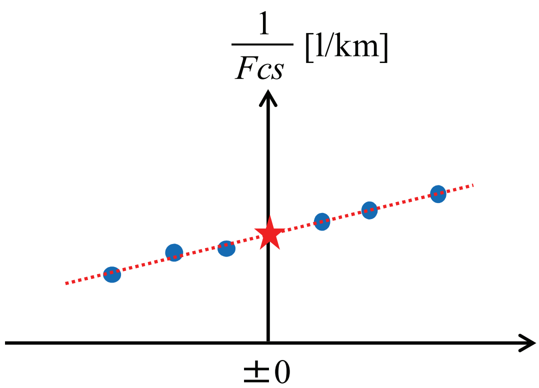

Figure2: Fuel Consumption Correction Calculation

3 Driving Simulation and Driving Test

3.1 Driving Simulation Outline

First, the driving simulation for evaluating the performance of a range extender-type PHV was constructed. Figure3 shows the simulation flow. The JC08 mode was used for the test cycle. This simulation allows the calculation of the inputs and outputs of each component, mileage, electrical mileage, and the like.

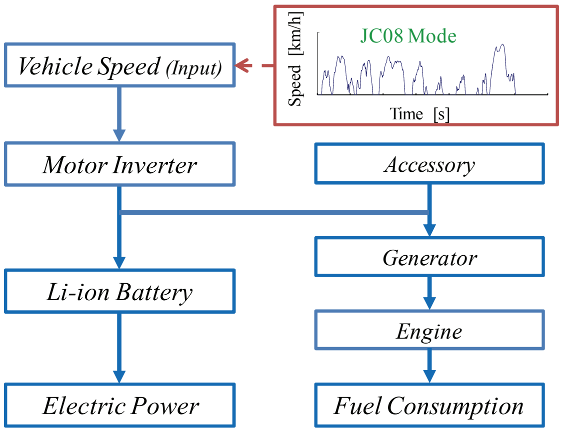

Figure3: PHV Simulation Model

3.2 Driving Simulation Results

Table4 shows the vehicle performance predicted by the simulation.
In CD mode, both the variable and constant control method adopts AE control. Therefore, CD range R_{CD} (=equivalent EV range R_{EV}), single charge electrical energy E_C, and electrical mileage E_{CR} have the same values for each control method. However, the results show that mileage with the constant control method is 5% better than the variable control method for CS mileage F_{CS} and combined mileage F_{PH}.

Table4: Vehicle Performance (Driving Simulation)

PHV Performance Index	Variable	Constant
R_{CD} [km]	15.0	15.0
F_{CD} [km/l]	—	—
F_{CS} [km/l]	21.9	23.1
F_{PH} [km/l]	32.7	34.5
E_C [kWh]	1.92	1.92
R_{EV} [km]	15.0	15.0
E_{CR} [km/kWh]	7.80	7.80

The graph in Figure4 shows an example of SOC, engine power, and vehicle speed trends for both control methods when the vehicle was driven through a JC08 test cycle in CS mode. Figure5 shows these engine usage points plotted on an engine map. With the constant control method, power is generated at the maximum engine efficiency point at or above that required to drive the vehicle. Therefore, the battery can be charged rapidly in a short period. In contrast, the variable control method determines the engine power in accordance with the accelerator angle. Therefore, SOC during driving is stable.

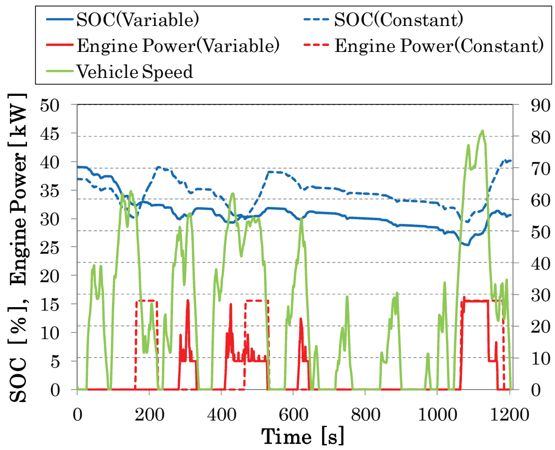

Figure4: Changes in SOC and Engine Power

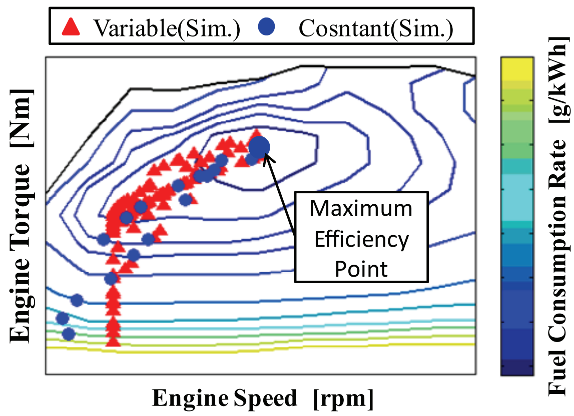

Figure5: Engine Torque and Engine Speed

3.3 Driving Test Results

In accordance with the test method of TRIAS, we conducted the CH-DY driving test on the target vehicle, and evaluated its performance.
By using CAN (Control Area Network), data logger, and CH-DY, we can get data such as the voltage and current of the component, as well as the fuel consumption, the driving force or the like.

Table 5 shows the results of the driving simulation and the driving test. By comparing them, it is confirmed that the values of each other in all indices are almost the same. In addition, we can find that the mileage performance of the constant control method is better than that of the variable control method at the driving test as well as the driving simulation. Specifically, the CS mileage F_{CS} and the combined mileage F_{PH} performance is superior by 7.9% and 7.6% than those with the variable control method.

Figure6 and Figure7 show some results of SOC, engine power, and vehicle speed for both controls when the vehicle was driven through a JC08 test cycle in CS mode. And Figure8 and Figure9 show the engine usage points plotted on an engine map. Each value between the driving simulation and the driving test has the close tendency. And by the above results, the accuracy of the driving simulation was confirmed.

Table5: Vehicle Performance

(Driving Simulation and Driving Test)

PHV Performance Index	Variable		Constant	
	Sim.	Test	Sim.	Test
R_{CD} [km]	15.0	14.3	15.0	14.3
F_{CD} [km/l]	—	—	—	—
F_{CS} [km/l]	21.9	21.5	23.1	23.2
F_{PH} [km/l]	32.7	31.6	34.5	34.1
E_C [kWh]	1.92	2.02	1.92	2.02
R_{EV} [km]	15.0	14.3	15.0	14.3
E_{CR} [km/kWh]	7.80	7.08	7.80	7.08

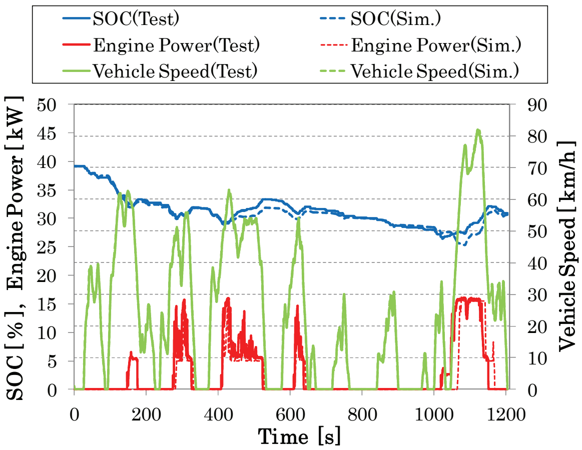

Figure6: Changes in SOC and Engine Power (Variable Control method)

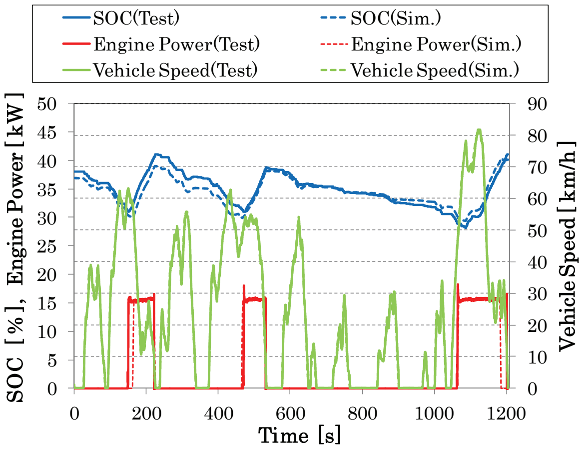

Figure7: Changes in SOC and Engine Power (Constant Control method)

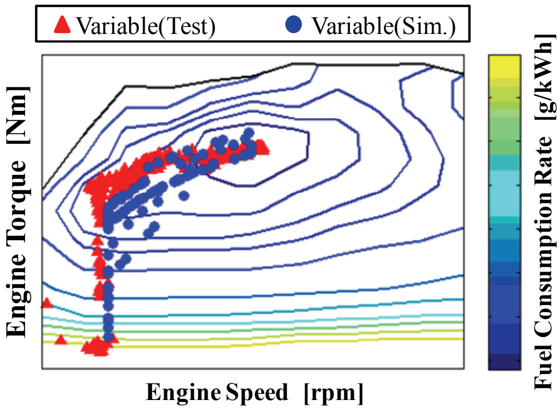

Figure8: Engine Torque and Engine Speed (Variable Control method)

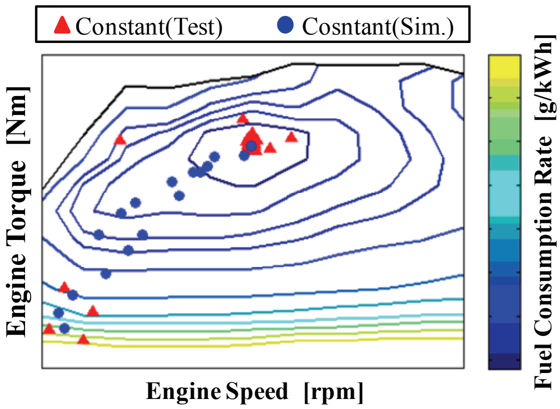

Figure9: Engine Torque and Engine Speed (Constant Control)

4 Energy Flow Analysis

Figures 10 and Figure11 show the energy flows between system components for both controls when the vehicle was driven through a JC08 test cycle in CS mode. Each loss of the components is calculated by the following equation.

○ Engine Loss L_{eng}

$$L_{eng} = f \cdot LHV - \int_0^t (T_{eng} \cdot \omega_{eng})dt \tag{4}$$

f : Fuel Consumption ,
LHV : Lower Heat Value of Gasoline
T_{eng} : Engine Torque,
ω_{eng} : Engine Revolution

○ Generator Loss L_{gen}

・Driving Simulation

$$L_{gen} = \int_0^t (1-\eta_{gen}) \cdot (T_{gen} \cdot \omega_{gen})dt \tag{5}$$

η_{gen} : Generator Efficiency,
T_{gen} : Generator Torque,
ω_{gen} : Generator Revolution

・Driving Test

$$L_{gen} = \int_0^t (T_{eng} \cdot \omega_{eng})dt - \int_0^t (I_{gen} \cdot V_{gen})dt \tag{6}$$

I_{gen} : Generator Current,
V_{gen} : Voltage of Generator

○ Battery Loss L_{bat}

$$L_{bat} = \int_0^t (I_{bat}^- \cdot V_{bat})dt - \int_0^t (I_{bat}^+ \cdot V_{bat})dt \tag{7}$$

I_{bat}^- : Battery Current under Discharging,
V_{bat} : Voltage of Battery Terminal,
I_{bat}^+ : Battery Current under Charging

○ AUX Loss L_{AUX}

・Driving Simulation

$$L_{AUX} = \int_0^t (P_{AUX})dt \tag{8}$$

P_{AUX} : Power Consumption of AUX = 250 W

・Driving Test

$$L_{AUX} = \int_0^t (I_{AUX} \cdot V_{bat})dt \tag{9}$$

I_{AUX} : Current from Main Battery to 12V Battery

○ Motor Loss L_{mot}

$$L_{mot} = \int_0^t (I_{mot}^- \cdot V_{mot})dt - \int_0^t (T_{mot}^+ \cdot \omega_{bat})dt + \{\int_0^t (I_{mot}^- \cdot V_{mot})dt - \int_0^t (T_{mot}^- \cdot \omega_{bat})dt\} \tag{10}$$

I_{mot}^+ : Motor Current under Driving,
I_{mot}^- : Motor Current under Braking,
V_{mot} : Voltage of Motor,
T_{mot}^+ : Motor Torque under Driving,
T_{mot}^- : Motor Torque under Braking,
ω_{mot} : Motor Revolution

○Transaxle Loss L_{trans}

・Driving Simulation

$$L_{trans} = \left(\frac{1}{\eta_{trans}} - 1\right) \cdot \int_0^t (F_{drive}^+ \cdot v)dt - (1-\eta_{trans}) \cdot \int_0^t (F_{drive}^- \cdot v)dt \tag{11}$$

F_{drive}^+ : Driving Force,
F_{drive}^- : Braking Force,
η_{trans} : Transmission Efficiency,
v : Vehicle Velocity

・Driving Test

$$L_{trans} = \int_0^t (T_{mot}^+ \cdot \omega_{mot})dt - \int_0^t (F_{drive}^+ \cdot v)dt - \{\int_0^t (F_{drive}^- \cdot v)dt - \int_0^t (T_{mot}^- \cdot \omega_{mot})dt\} \tag{12}$$

In these flows, inputs, outputs, losses, and other energy amounts are shown as percentages, with the quantity of heat generated by the consumption of gasoline defined as 100. The constant control method has lower engine loss but greater battery loss than the variable control method. Constant control method is capable of reducing engine loss since it maintains engine operation at the maximum efficiency point. However, this also increases the battery loss because of the greater charge and discharge power of the battery. Figure 12 shows the results of the driving simulation performed to illustrate this phenomenon, i.e., the increase in battery charge and discharge losses under the constant control method.

These engine and battery losses have a major impact on the performance of a range extender-type PHV. Although there is a trade-off relationship between the two, the constant control method is more suitable for the vehicle studied in this research since reducing engine loss has a much stronger effect on vehicle performance.

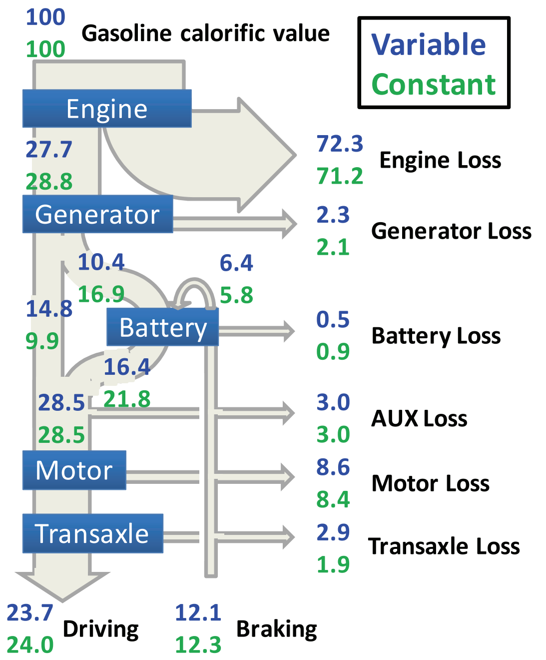

Figure10: Energy Flow of the Driving Simulation

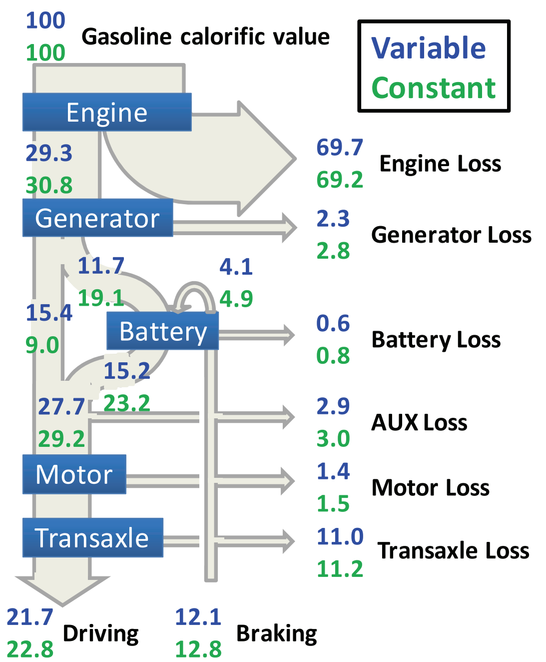

Figure11: Energy Flow of the Driving Test

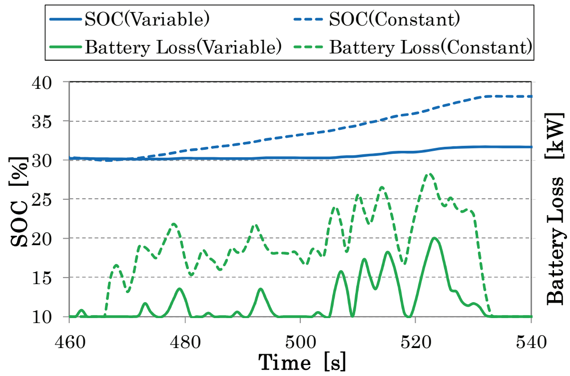

Figure12: SOC and Battery Loss

5 Conclusion

This research compared a range extender-type PHV operated under two different control methods: the constant control method, which drives the engine at a constant maximum efficiency, and the variable control method, which drives the engine in accordance with the vehicle load. The comparison results quantitatively verified that the constant control reduced engine loss but caused battery loss to increase. However, since the best control method is determined by the engine and battery loss characteristics of the target vehicle, the constant control method enables superior mileage for the vehicle examined in this research due to its large engine loss reduction effect. In our case, 7.9% improvements of the charge sustaining mode mileage F_{CS} and 7.6% improvements of the combined mileage F_{PH} have been achieved by adopting the constant control method.

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