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Environmental Performance Evaluation of Plug-in Hybrid Electric Vehicles

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Abstract

This paper describes a dynamic simulation model built to assess Plug-in Hybrid Electric Vehicles (PHEVs) performance and lithium-ion battery performance installed in PHEVs. First, we examine vehicle performance. In particular, the effects of engine on/off controls and the effects of drive distance are evaluated, because they have significant impact on PHEVs environmentally friendly performance. A study of cycle life test methods for batteries installed in PHEVs is also examined. Here, we discuss the establishment of a common PHEV battery charge/discharge test profile for Japan, the US, and Europe.

Keywords: battery, environment, PHEV (plug in hybrid electric vehicle), simulation

1 Introduction

Plug-in Hybrid Electric Vehicles (PHEVs) incorporates electric drive using charged external grid power into conventional Hybrid Electric Vehicles (HEVs). The resulting vehicle system achieves zero-emission performance over short distance driving equivalent to pure electric vehicles. Because of this fact, hope of its early practical application is building, and development is firmly underway in Japan, the US, and Europe. However, the environmental performance of PHEVs varies greatly according to the drive distance. Therefore, any decision about whether to bring PHEVs to the market must be determined based on performance evaluation using actual driving conditions.

This paper presents the following points: 1) a report on the environmental performance of PHEVs in view of drive distance, and 2) a study of test methods for batteries to be installed in PHEVs. Point 1 evaluates the effects of changes in engine controls on fuel efficiency, and point 2 discusses the establishment of a common PHEV battery charge/discharge test method for Japan, the US, and Europe.

2 PHEV Modeling

2.1 PHEV Modeling Overview

By using the New European Driving Cycle (NEDC) and other homologation driving schedules as inputs, a model was constructed that is capable of calculating time-based changes in engine/motor output, current/voltage/state of charge (SOC) of the battery, fuel consumption, CO_2 emissions, and the like. An outline of the model is shown in Figure 1 [1]. The simulation results presented in this paper were obtained using this PHEV model, which was created with MATLAB/Simulink.

2.2 Driving Schedules

In consideration of vehicle use conditions, which differ from region to region, homologation driving schedules for Japan (JC08), the US (UDDS), and Europe (NEDC) were used to run numerical simulations. The relation between speed and time of each driving schedules is Figure 2.

2.3 Vehicle Specifications

The specifications of the simulated vehicle are shown in Table 1 [2]. The vehicle was a widely used regular five-person passenger car and the hybrid system was a series/parallel-type incorporating a planetary gear mechanism.

2.4 Engine 'On' and 'Off' conditions

The used SOC range was from 90% to 30%. The engine's on/off status was controlled by the 4 kind of trigger conditions shown in Table 2; if just one condition were satisfied, the engine would turn on. Conditions were made to change whenever SOC crossed the 35% level. Therefore, Charge Depleting (CD) mode was from 90 through 35%, and Charge Sustaining (CS) mode was under 35% [3].

2.5 Methods for Determining Engine Power Output

Engine power output was determined using the following equation.

$$P_{req} = P_{drive} + P_{add} \quad (1)$$

$$P_{add} = p \cdot (SOC_{target} - SOC) \quad (2)$$

$$\text{provided that, } P_{add} \geq 0$$

where,
P_{req}: power required for maximum engine output [W]
P_{drive}: power required for driving force [W]
P_{add}: power required for battery charging [W]
p: power-charging coefficient [W]
SOC_{target}: target SOC 35%
SOC: current SOC

By determining power output in this way, driving that consistently holds to the target SOC could be achieved. This result makes it possible for HEV driving with a limited SOC range.

2.6 Methods for Determining Planetary Gear Mechanism Rotation Speed and Torque

A planetary gear model was used to split power. The generator was installed with a sun gear, the engine with the planetary gear carrier and the motor with a ring gear, and all three mechanisms were connected. The following relational equation expresses the rotation speed [4].

$$N_g = \left(1 + \frac{Z_m}{Z_g}\right) \times N_e - \left(\frac{Z_m}{Z_g}\right) \times N_m \quad (3)$$

$$Z_m = Z_g + Z_e \quad (4)$$

where,
N: rotation speed
Z: number of gear teeth
g: generator (sun gear)
e: engine (planetary gear)
m: motor (ring gear)

The ring gear was directly connected to the output shaft so that its rotation speed was determined by the vehicle speed. Generally in simulations, the engine power output is determined first and then the engine's rotation speed is calculated to achieve efficient driving. Having determined the engine power output and rotation speed, torque was obtained from Equation 5 and other torque calculations are shown in Equation 6.

$$T_e = \frac{P_{req}}{N_e} \quad (5)$$

$$T_g = \frac{Z_g}{Z_m + Z_g} \times T_e$$
$$T_m = T_d - \frac{Z_m}{Z_m + Z_g} \times T_e \quad (6)$$

where,
T: torque
d: drive shaft

3 Simulation Evaluation Results of PHEV Environmental Performance

3.1 Differences in Environmental Performance Depending on Engine On/Off Control

The amount of CO_2 emissions was used as an index to assess environmental performance because this enables the amount of emissions to be determined not only during driving but also during electricity generation. In this paper, external charging energy refers to the energy amount required to recharge the battery to an SOC of 90% after driving. The equation below was used for calculations [5].

$$m_{CO2} = \frac{a_g \times V + \frac{a_e}{\eta_e} \times U}{d} \quad (7)$$

where,
m_{CO2}: CO_2 emissions [g-CO_2/km]
d: driving distance [km]
V: gasoline consumption [L]
U: electricity consumption [kWh]
(external battery charging output)
a_g: CO_2 emissions coefficient (gasoline) 2,380 g/L
a_e: CO_2 emissions coefficient (electricity) 375 g/kWh
η_e: power transmission efficiency 0.953
(Values take into account all the processes involved from the mined source material)

First, the impact of the engine on/off control method on CO_2 emissions was studied in the JC08. In this study, a target drive distance d of 8.17 km was adopted to complete one cycle of JC08. The calculation results are shown in Figure 3.

Relative to the base HEV, in all-electric range (AER), which involves driving throughout the entire cycle on battery power alone, a 40% reduction in CO_2 was achieved. The greatest CO_2 reduction was observed when the control was switched from Bld_6kW to Bld_12kW when using the Bld control. As shown in Figure 4, this is because the total time that the vehicle is driven at a power between 6 kW and 12 kW is greater than the driving time over 12 kW in the JC08.

3.2 Changes in Environmental Performance According to Drive Distance

The fuel and electricity consumption of a PHEV varies significantly according to the drive distance. This section studies the impact of the drive distance on CO_2 emissions in repeated driving schedule of JC08. Figure 5 shows that driving as close as possible to AER enhances environmental performance in short-distance driving. Meanwhile, differences in the effect of engine on/off control on CO_2 emissions virtually disappear in drive distances over approximately 100 km.

Figure 6 shows the eleven categories determined for the daily drive distance of passenger cars in Japan [6]. It also shows that approximately 80% of users drive 43 km or less per day. This is represented by the area outlined with a dotted line, and corresponds to categories A to D. Evaluation of these categories reveals that environmental performance markedly improves when an engine on/off control of Bld_12kW or more is adopted, and that a Bld_6kW control does not provide much benefit. It appears that when providing PHEVs to the market it will be necessary to adjust the engine on/off control to suit the actual daily drive distance of users.

While it is understood that a PHEV with a Bld_12kW engine on/off control yields better environmental performance than one with a Bld_6kW control, as shown in Figure 7 it should be noted that the battery SOC drastically drops for vehicles that adopt a control of Bld_12kW or more. In general, it has been noted that sharp changes in SOC deteriorate battery life. This is an area that will be further studied in the future.

4 Examination of PHEV Li-ion Battery Charge/Discharge Test Methods

4.1 Understanding Battery Power Density Characteristics by Driving Schedules

This paper assumes that a 3 kWh battery (10 Ah, 300 V, 30 kg) is installed in the PHEV. Figures 8 (a) to (c) show the battery power density calculated using inputs obtained from the Japanese, US, and European homologation driving schedules. A distinctive point of the JC08 is that the maximum output is smaller than for the UDDS and NEDC. The large overall battery power in the UDDS is due to the larger acceleration/deceleration slope. A feature of the NEDC is the requirement for high power density in the high-speed driving range after 800 seconds.

Next, the maximum power density was examined to understand the maximum load on the battery in the driving schedules of each region (Figure 8 (d)). In AER, which involves driving in all ranges on battery power alone (i.e., the engine is turned off all time), the battery maximum power density of 871 W/kg that was achieved in the JC08 is smaller than that for UDDS and NEDC (1338 W/kg and 1328 W/kg, respectively). However, it was found that with Bld control, which involves driving from both power electric motor and engine, the difference among the maximum power densities of each driving schedules was less significant. Bld_6kW was excluded from the evaluation because it was verified that it does not enhance environmental performance.

4.2 Battery Power Density Frequency Analysis by Driving Schedules

Figure 9 shows the battery power density distributions in each driving schedule. By focusing on the power density distributions, it should be possible to identify changes in battery load throughout an entire driving schedule. The data is sorted in descending order and not by time in each schedule.

Next, the integral values of the power results in Figure 9 (at discharge) were compared (Figure 10). The integral values represent discharge energy per unit mass of the battery used in one cycle of each driving schedule. Figure 11 shows that as the engine engagement ratio grows, the dispersion in discharge energy per unit mass among driving schedules becomes small. Therefore, battery load throughout a cycle does not vary significantly among the schedules used in Japan, the US, and Europe in the case of Bld control.

4.3 Charge/Discharge Test Profile Selection

The previous section described that the PHEV battery power levels in the cycles of three regions (Japan, the US, and Europe) became closer as the engine engagement ratio increases. This section examines a charge/discharge cycle life test method that can be used as a standard method across the three regions. The concept of the charge/discharge profile is typical and simple. The following is the procedure for establishing a charge/discharge profile.

1) To take into account the charge/discharge trends of PHEV batteries in Japan, the US, and Europe comprehensively, sort battery power density values (W/kg) in descending order regardless of the driving schedule (JC08, UDDS, NEDC).

2) To simplify the charge/discharge test profile, compress the cycle duration from start to finish to 90 seconds.

3) Convert the sorted and compressed data from steps 1) and 2) (hereinafter referred to as "compressed data") into a rectangular wave (Figure 12). The rules for the rectangular wave conversion are as follows.

a. The wave should be adjusted in increments of 2 seconds and 100 W/kg.

b. The peak value should be obtained by rounding off the mean value of the five highest items to the nearest 100 W/kg.

c. Power density less than ±50 W/kg should be treated as zero.

d. The total charge/discharge energy per unit mass (Wh/kg) should equal the total charge/discharge energy of the compressed data.

e. The discharge ranges in CD mode should be peak, medium (400 W/kg), and minimum (100 W/kg) and the power ranges in CS mode should be peak and minimum (100 W/kg). There should be two charge ranges for both modes.

4) Align the charge/discharge profiles from the vehicle starting acceleration (start of discharge) to deceleration stop (end of regenerative charge) and switch the inverted L shape that represents charging time into a non-inverted L shape (Figure 13). This completes the procedure.

5 Conclusions

a) A driving simulator was built simulating a PHEV drive system and control methods. Specifically, a PHEV model was created adopting a series/parallel hybrid system with a planetary gear mechanism.

b) This model was used to simulate and evaluate the environmental performance of a PHEV. Using CO_2 emissions as an index, the impacts of the engine on/off control and drive distance on the environmental performance were analyzed using a Japanese driving schedule. It was proven that extending the 100% electric driving range (electric drive power of 12kW and over in this study) to a certain extent achieved excellent environmental performance.

c) Using the results obtained from the simulation tests, a PHEV Li-ion battery charge/discharge test method was studied in view of driving in Japan, the US, and Europe. A simplified test profile was created by analyzing battery power density distribution in each driving schedule, sorting the data, and compressing it into 90 seconds.

Acknowledgments

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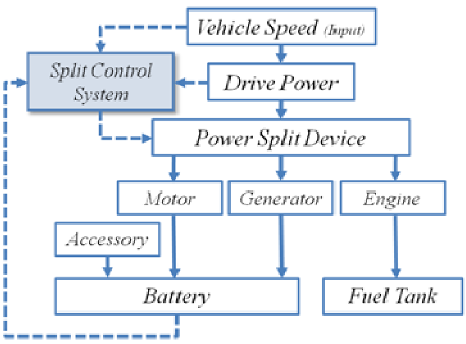
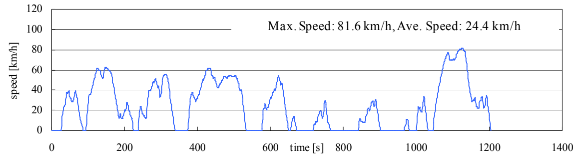
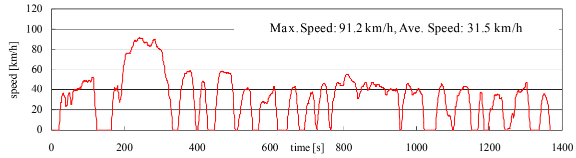


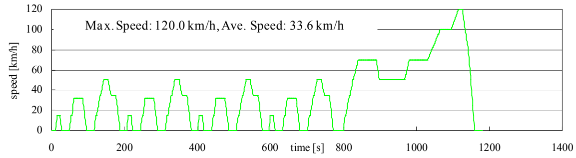
Figure 1: Simulation Model



(a) JC08_JAPAN



(b) UDDS_USA



(c) NEDC_EU

Figure 2: Driving Schedules

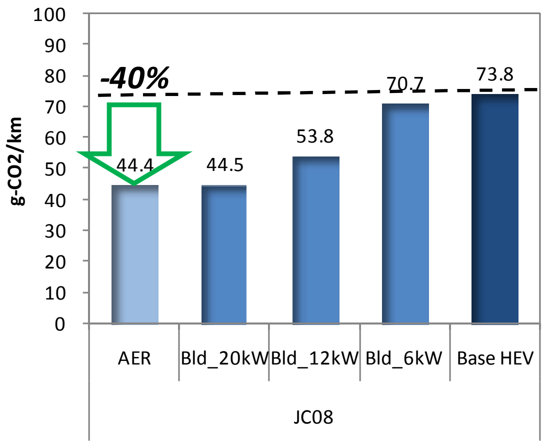


Figure 3: CO_2 Emissions Depending on Engine On/Off Control

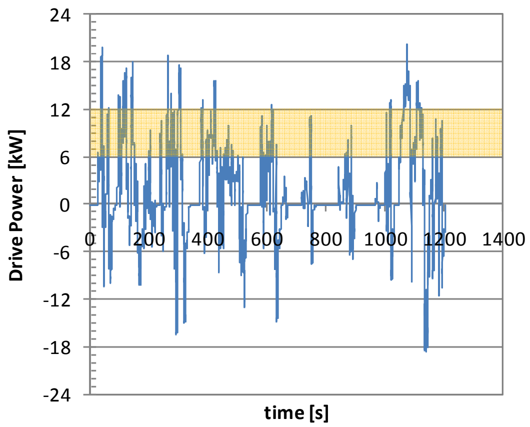


Figure 4: Drive Power Necessary for JC08

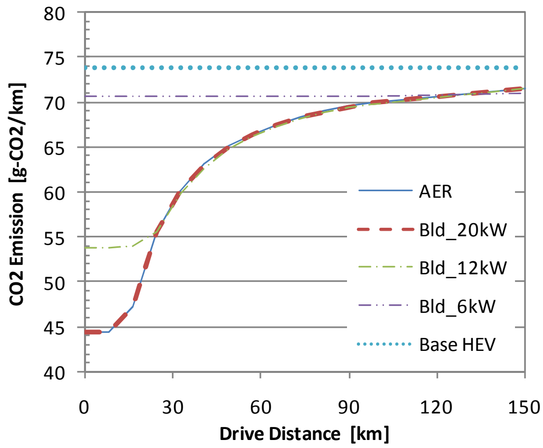


Figure 5: CO_2 Emissions (Distance-Dependent)

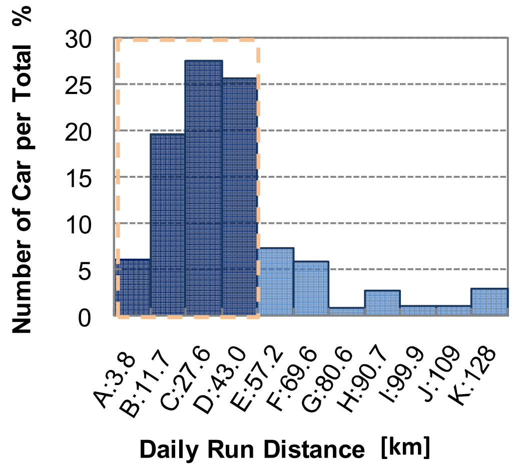


Figure 6: Daily Drive Distance of Passenger Cars in Japan

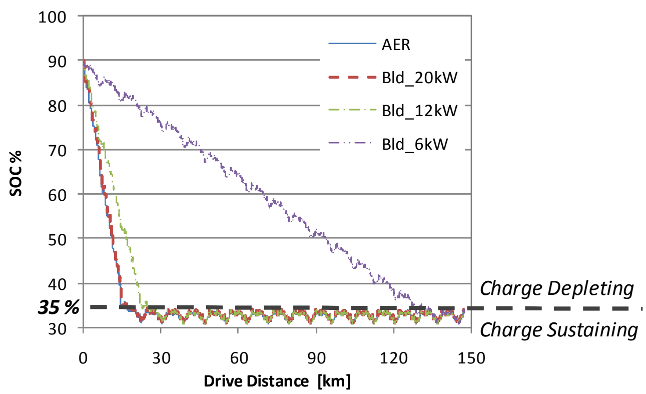
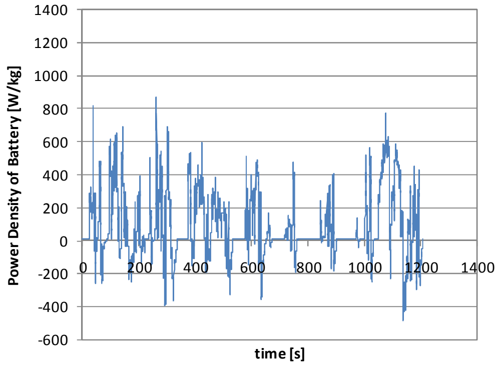
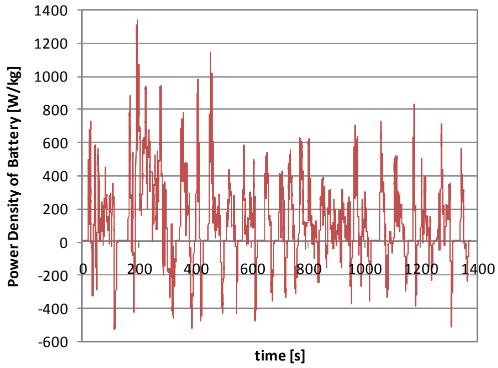


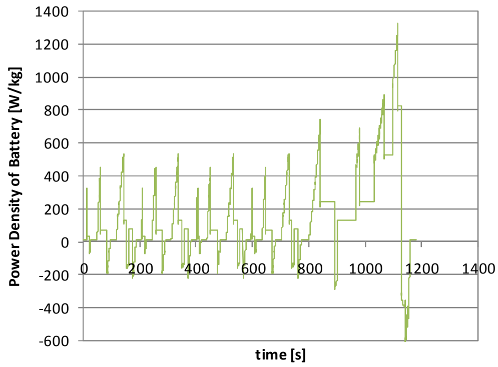
Figure 7: Time-Based SOC Changes



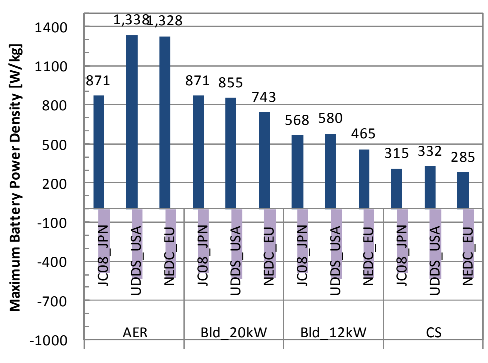
(a) JC08_JAPAN



(b) UDDS_USA

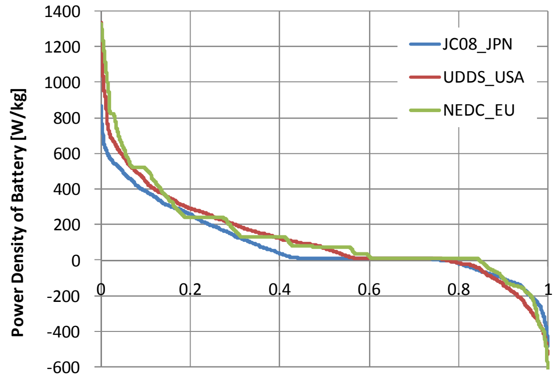


(c) NEDC_EU

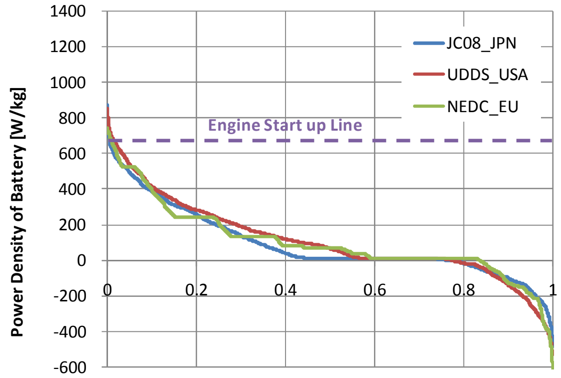


(d) Maximum Battery Power Density

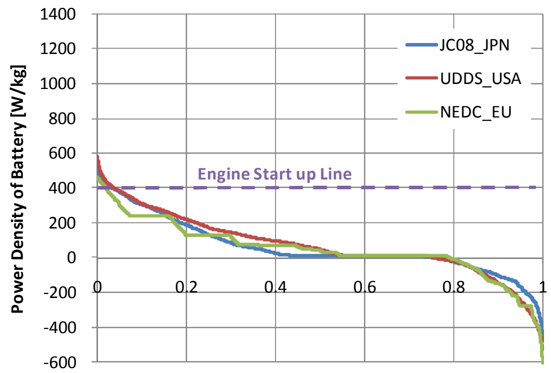
Figure 8: Battery Power Density by Driving Schedule



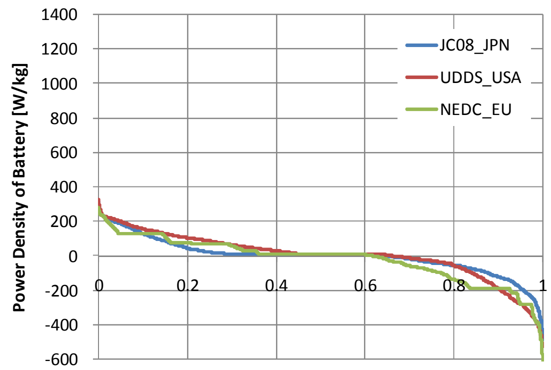
(a) AER



(b) Bld_20kW



(c) Bld_12kW



(d) Charge Sustaining

Figure 9: PHEV Battery Power Density Distributions*1

*1: The reason why power density higher than the engine start up line is generated is because motor efficiency is added to the required drive power.

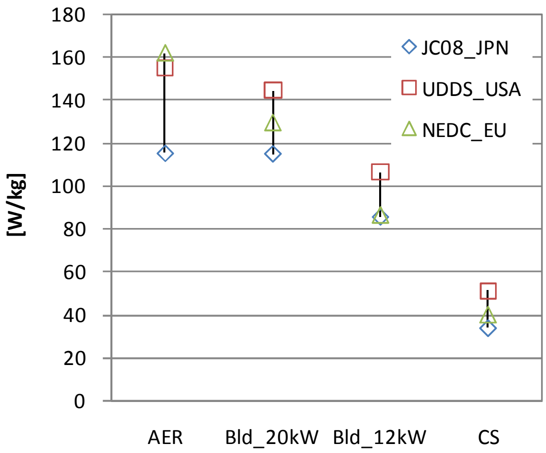


Figure 10: Comparison of Discharge Energy Amounts per Unit Battery Mass

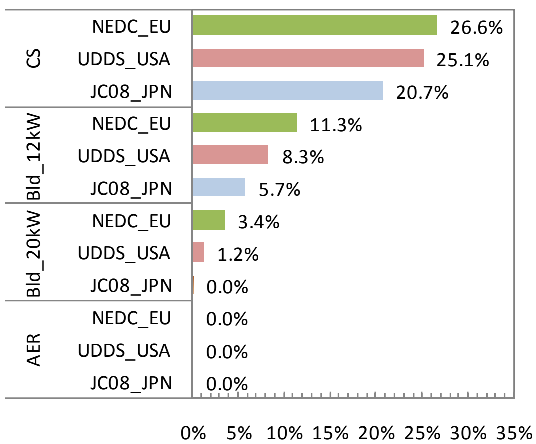
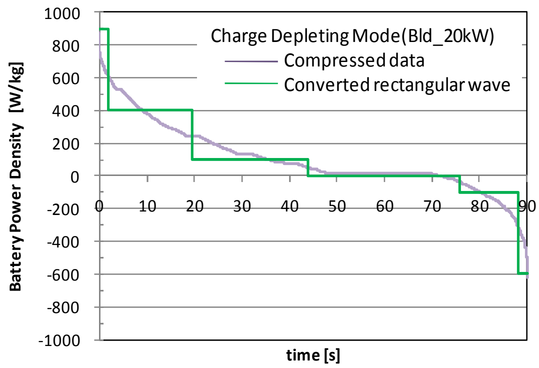
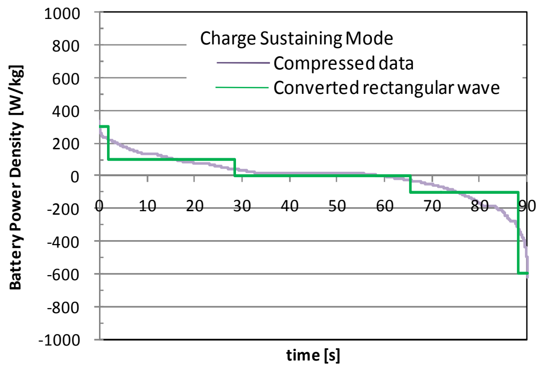


Figure 11: Comparison of Engine Engagement Ratios*2

*2: Percentage of engine engagement in total driving time

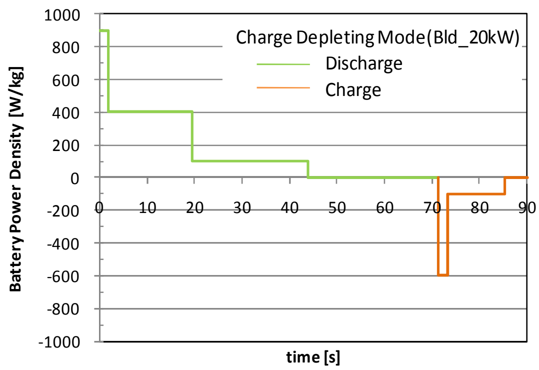


(a) CD Mode

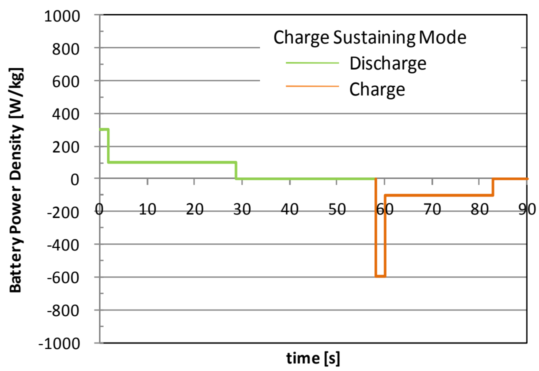


(b) CS Mode

Figure 12: Charge/Discharge Profile Study (Up to Step 3)



(a) CD Mode



(b) CS Mode

Figure 13: Charge/Discharge Profile Study (Final Version)

Table 1: Vehicle Specifications [2]

Parameter			Set value
Mass	Vehicle mass	kg	1250
	Equivalent rotational part mass		43.75 (3.5% of vehicle mass)
	Passenger mass		110
Road load	Rolling resistance coefficient	-	0.01
	Air resistance coefficient	N/(km/h)^2	0.0343
Powertrain efficiency	Motor efficiency	-	[from data base] *2
	Transmission efficiency	-	0.95
	Final gear efficiency	-	0.95
Battery system	Rated capacity	Ah	10
	Battery mass	kg	30
	Voltage	V	[300]*2
	Maximum power	kW	60
	Discharge efficiency	-	[from data base] *2
	Charge efficiency	-	[from data base] *2
	SOC range*1	%	90-30
Other	Braking method	-	Regenerative brake Friction brake

*1: SOC : State Of Charge　*2: Data of Waseda Univ.

Table 2: Engine Startup Conditions

Mode	CD: SOC≧35 %	CS: SOC＜35 %
AER*1	Engine stop all time (only Motor Power)	Drive Power: 6 kW or over SOC: Under 30 %
Bld_20kW*2	Drive Power: 20 kW or over	Drive Power: 6 kW or over SOC: Under 30 %
Bld_12kW*2	Drive Power: 12kW or over	Drive Power: 6 kW or over SOC: Under 30 %
Bld_6kW*2	Drive Power: 6 kW or over	Drive Power: 6 kW or over SOC: Under 30 %

*1: All Electric Range Mode　*2: Blended Mode

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