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Green Driving Assistance System for Heavy-Duty Hybrid Electric Vehicle

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Summary

This paper describes development of a new Green Driving Assistance System. The author developed the system to achieve further improvement of the fuel efficiency of HEVs (Hybrid Electric Vehicles). This system reduces driver’s unnecessary acceleration and deceleration of the vehicle based on the information of vehicle speed and inter-vehicle distance. This system is available on almost all kind of roads such as local roads, highways and limited-access roads in a car-following situation, without causing driver drivability stress.

Keywords: optimization, HEV, power management, energy consumption, truck

1 Introduction

This paper describes development of a new Green Driving Assistance System. The author developed the new system to achieve further improvement of the fuel efficiency of HEVs.

The author develops HEVs to improve fuel efficiency. Green Driving utilized the characteristics of HEVs maximize fuel efficiency improvement effect of HEVs. However, for most of drivers, to perform Green Driving consciously is quite difficult. Therefore, the author set the purpose of this development as establishing an on-board system which assists the driver's Green Driving and improves the fuel efficiency of HEVs.

“Preceding-vehicle follow-up” control called ACC (Adaptive Cruise Control) is very famous an existing technology. ACC emphasizes responsiveness. Also, it is available on kind of roads such as highways and limited-access roads. On the other hand, the purpose of the author's development is to improve fuel efficiency of HEVs. In addition, the target vehicle mainly drives in an urban area. Therefore, the author defined two development goals of the new system as follows. One is to improve fuel efficiency and to have responsiveness without causing drivability stress. The other is to be available on almost all kind of roads such as local roads, highways and limited-access roads in a car-following situation.

The author analyzed the driving data of Green Driving and normal driving acquired during an actual vehicle test and clarified that Green Driving utilized the characteristics of HEVs can improve fuel efficiency. In addition, as a result of the driving data analysis, the author clarified that Green Driving has a characteristic of less fluctuation frequency in vehicle speed than normal driving. Based on the mentioned findings, the author concluded that the factor of difference between Green Driving and normal driving is that Green Driving has less “high frequency component of the vehicle speed” than that of normal driving.

Thus, the author decided that the goal of the new system is to assist the driver's operation to have responsiveness without causing drivability stress and to reduce “high frequency component of the vehicle speed” in a car-following situation.

The author designed the new system by installing an driver model optimized for Green Driving (optimum driver model) that realizes Green Driving utilized the characteristics of HEVs in a “preceding-vehicle follow-up” model. The author designed the control model of the optimum driver model to be the same as that of the base driver model. The author designed the driver characteristic parameter as the optimum value to realize the Green Driving utilized the characteristics of HEVs. The author set the target value of the “cut-off frequency of the vehicle speed” of the optimum driver model from the result of an actual vehicle test. The author verified that the “cutoff frequency of the vehicle speed” of the new system can assist the driver's operations with the “cut-off frequency of the vehicle speed” according to the target value through an actual vehicle test.

The author verified the effectiveness of the fuel efficiency improvement of HEVs by the new system through MATLAB simulation and an actual vehicle test.

2 Background

2.1 Purpose of this development

The author develops HEVs to improve fuel efficiency. Green Driving utilized the characteristics of HEVs maximize fuel efficiency improvement effect of HEVs. However, for most of drivers, to perform Green Driving consciously is quite difficult. Therefore, the author set the purpose of this development as establishing an on-board system which assists the driver's Green Driving and improves the fuel efficiency of HEVs.

2.2 Target vehicles

The target vehicle is HEVs which are a heavy-duty vehicle equipped with a parallel hybrid electric system. Gross vehicle weight is less than 8 tons (Fig. 1, Fig. 2).

The main components of HEVs are an electric motor/generator, an inverter and a high voltage battery, in addition to a diesel engine, a clutch and an automated manual transmission, which are common components with ICVs (conventional Internal Combustion Vehicles).

HEVs can consume less fuel than ICVs in following deceleration and acceleration cycles. During deceleration, the motor operates as a generator and transform the braking energyof the vehicle into electric energy. The electrical energy is temporarily stored in the high voltage battery. During acceleration, the motor transforms the stored electric energy into kinetic energy and the motor supplies the kinetic energy to rotate the drive shaft. The motor can reduces the energy from the engine by its own energy. For detailed principles, please refer to the reference [1].

Figure1: Target vehicle appearance

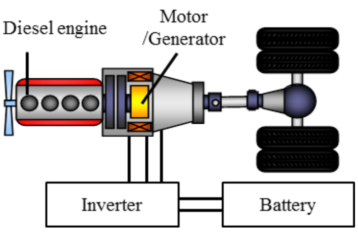

Figure2: Parallel hybrid electric system

2.3 Advantage over existing technologies

As an existing technology, "preceding-vehicle follow-up" control called ACC is very famous. ACC emphasizes responsiveness. Also, it is available on kinds of roads such as highways and limited-access roads.

Conventional technology of our company is known as a control to through Low Pass Filter (LPF) which controls driver's accelerator operation with on-board system. The control improves fuel efficiency by reducing unnecessary vehicle speed fluctuations by constantly passing the driver's accelerator operations through a LPF.

On the other hand, the purpose of the author's development is to improve fuel efficiency of HEVs. Also, the target vehicle mainly drives in an urban area. Therefore, in the new Green Driving Assistance System, the author aims to improve not only fuel efficiency but also responsiveness without causing drivability stress. In addition, the system should be available on almost all kind of roads such as local roads, highways and limited-access roads in a car-following situation.

In summary, the advantages of the new system over the existing technology are following three points: (1) Improved fuel efficiency; (2) Available on almost all road kinds; (3) Low drivability stress.

3 Specify factors of fuel efficiency difference

In order to achieve the objective of improving fuel efficiency of HEVs, the author analysed different driver's driving data focusing on the difference of fuel efficiency. The author identified factors which cause its difference.

The analysis procedure is as follows. First, the author acquired driving data with different drivers' operations through actual vehicle test. Second, the author compared the fuel efficiency of the driving data and clarified the influence of driver's operation on fuel efficiency. Finally, the author focused on the fuel efficiency difference and analysed the driving data to identify the factor which caused the difference in fuel efficiency.

3.1 Driving data acquisition

The author acquired driving data with different drivers' operations through an actual vehicle test. In the test, the nine test drivers drove once each without Green Driving instruction (normal driving) and with Green driving instruction (Green Driving). The route of all the tests is the same urban route in Japan, and the test vehicle was a HEV which is a heavy-duty vehicle.

3.2 Comparison of fuel efficiency

The author collected the acquired driving data and compared fuel efficiency. The result showed that the fuel efficiency of Green Driving was 12.8% less than that of normal driving (Fig. 3). Also, the result showed that Green Driving utilized the characteristics of HEVs can improve fuel efficiency.

In addition, the author analysed and compared the acquired data focusing on energy. The result showed that the acceleration energy of Green Driving was 11.5% less and the regenerative energy of Green Driving was 12.4% higher than those of the normal driving (Fig. 4).

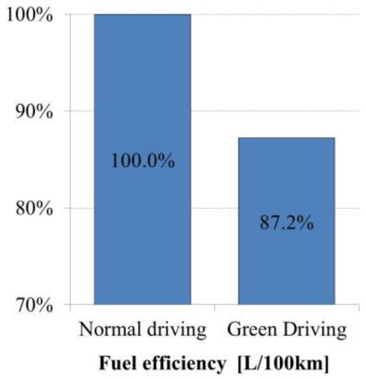

Figure3: Fuel efficiency

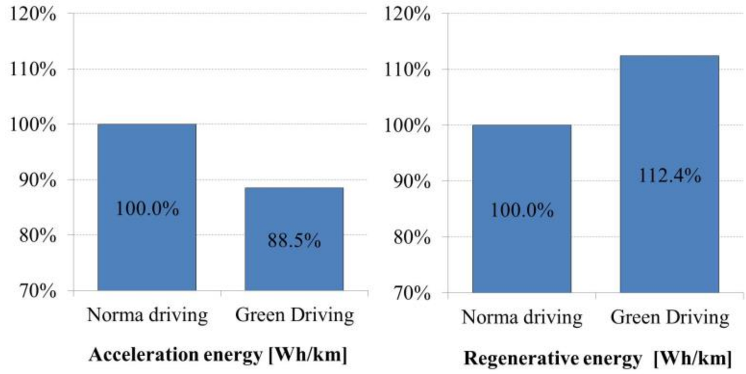

Figure4: Vehicle energy

3.3 Factor analysis of fuel efficiency difference

The author analysed the acquired driving data focusing on fuel efficiency difference. Generally, when the acceleration energy is low and the regenerative energy is high, the fuel efficiency of HEVs becomes low. Therefore, the energy difference shown in Section 3-2 is a factor of the difference fuel efficiency of HEVs.

In order to identify the factor of the energy difference, the author compared the time-series record of vehicle speed in the driving data. As a result, the author found that Green Driving has less frequency of fluctuation in vehicle speed than that of normal driving (Fig. 5).

Next, in order to clarify the difference in the frequency of fluctuation of the vehicle speed between Green Driving and normal driving, the author converted the vehicle speed time series data of the driving data into PSD and analysed.

As a result, it is revealed that Green Driving has a less "high frequency component of vehicle speed" than that of normal driving (Fig. 6). In general, the PSD of the vehicle speed increases the low frequency component in driving with less frequency of acceleration, such as steady state, and increases the high frequency component in driving with higher frequency of acceleration.

Figure 5 shows a part of the vehicle speed time-series data, which is a certain test driver acquired during the test.

Figure 6 shows the vehicle speed data in Fig. 5 converted to PSD and shown for each frequency. Figure 6 represents the difference in energy density occupied by each frequency component of the vehicle speed.

As a result of above analysis, the author concluded that the factor of fuel efficiency difference between Green Driving and normal driving is to keep the “high frequency component of the vehicle speed” of Green Driving less than that of the normal driving.

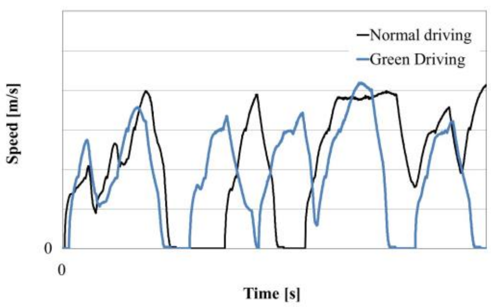

Figure5: Test data of vehicle speed

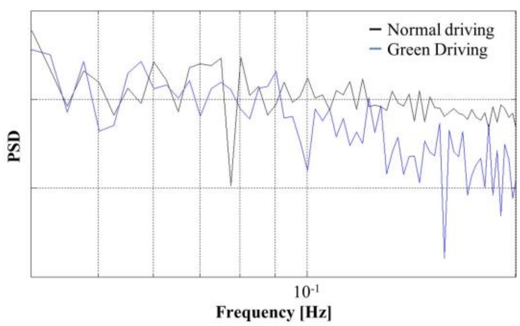

Figure6: PSD of vehicle speed

4 Overview of Green Driving Assistance System

4.1 Development goal

The analysis result of Chapter 3 concluded that the factor of fuel efficiency difference between Green Driving and normal driving is to keep the “high frequency component of the vehicle speed” of Green Driving less than that of the normal driving.

However, too less “high frequency component of the vehicle speed” causes drivability stress. With the new Green Driving Assistance System, the author aims to have responsiveness without causing drivability stress and to improve fuel efficiency. In addition, the author aimed to secure availability of the new system on almost all kind of roads such as local roads, highways and limited-access roads, in a car-following situation.

Therefore, the author set assisting the driver's operation to have responsiveness without causing drivability stress and reducing the “high frequency component of the vehicle speed” in a car-following situation as the goal of the new system development.

4.2 Design concept

The new Green Driving Assistance System assists driver's accelerator operation and driver's brake operation. In the new system, the optimum driver operation is calculated by feedback control of vehicle speed and inter-vehicle distance (Fig. 7).

The ACC known as an existing technology realizes a “preceding-vehicle follow-up” control with high responsiveness by automatically controlling the accelerator operation and the brake operation. The automatic driver operation is calculated by feedback control of the vehicle speed and the inter-vehicle distance (Fig. 8).

The acceleration LPF control which is our conventional technology realizes good fuel efficiency by constantly passing the driver's accelerator operation through the LPF (Fig. 9).

Although there is a trade-off relationship between fuel efficiency and responsiveness, the new system aims to both improve fuel efficiency and realize sufficient responsiveness.

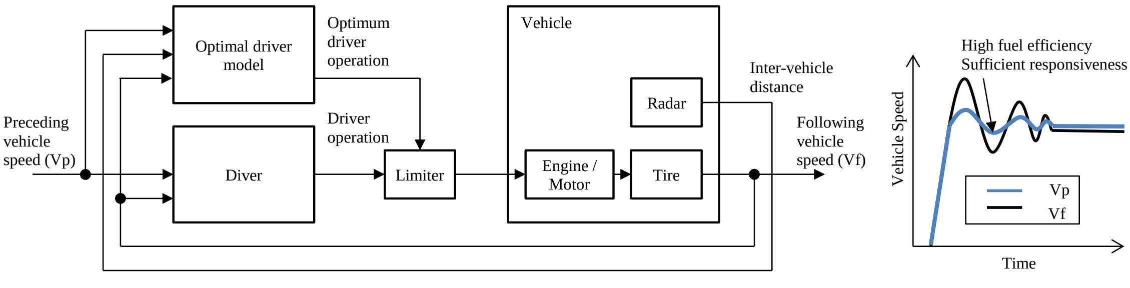

Figure7: Simplified control model of Green Driving Assistance System

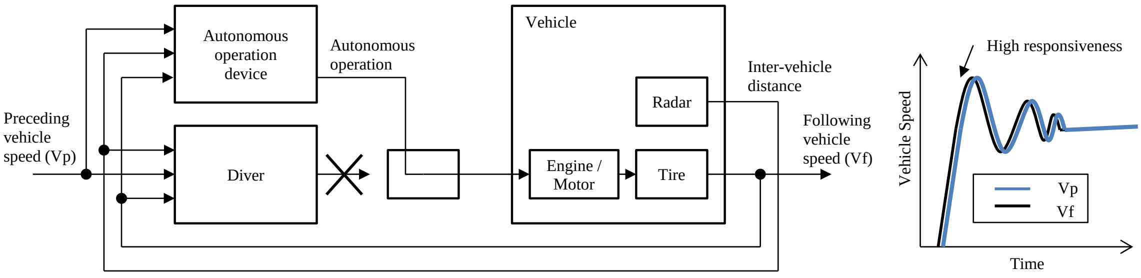

Figure8: Simplified control model of ACC

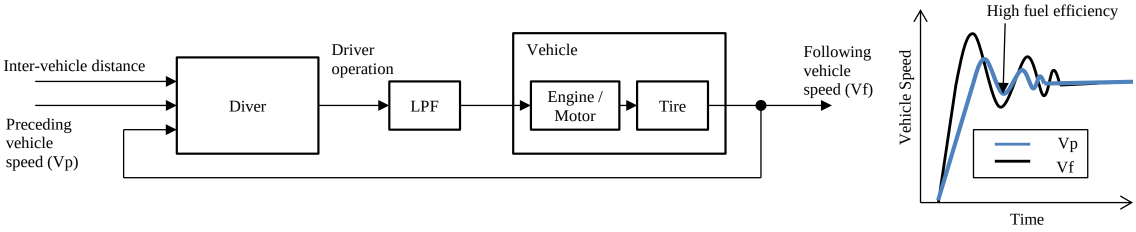

Figure9: Simplified control model of acceleration LPF control

5 Design of Green Driving Assistance System

The author designed the new Green Driving Assistance System by installing an optimum driver model for Green Driving utilized the characteristics of HEVs in a “preceding-vehicle follow-up” model.

The design procedure of the new system is as follows. First, the author defined the base driver model. Second, the author designed an optimum driver model and installed it in the base driver model. Third, the author determined the target value of “cut-off frequency of vehicle speed” through the actual vehicle test. Fourth, the author matched the driver characteristic parameters in the optimum driver model as target values of the “cut-off frequency of the vehicle speed”. Then, the author installed the new system in the on-board system. Finally, the author verified the “cut-off frequency of the vehicle speed” of the new system through an actual vehicle test.

5.1 Definition of base driver model

The author defined the base driver model. Fig. 10 shows the “preceding-vehicle follow-up” model (Table 1). The input is the preceding vehicle speed and the feedback value of following vehicle speed and the output is the following vehicle speed.

The author designed the model based on the base driver model in the “preceding-vehicle follow-up” model (Fig. 10). The inputs in the “preceding-vehicle follow-up” model are relative speed, inter-vehicle distance and following vehicle speed, and the output is the driver operation. The driver operations are accelerator operation as positive side and brake operation as negative side. The purpose of the base driver model is to simulate the driver operation based on the relative relation such as the relative speed and the inter-vehicle distance.

The relationship between the input and output of the base driver model varies depending on the driver, but by matching the driver characteristic parameters (Gv, Gx, Th), the relationship between the input and output of the base driver model become almost the same as that of the driving simulator (Suzuki et al.)[2].

5.2 Design of optimum driver model

The author designed the optimum driver model to realize Green Driving utilized the characteristics of HEV and installed the optimum driver model in the “preceding-vehicle follow-up” model. Then, the author set the control model of the optimum driver model as the base driver model, and matched the driver characteristic parameters to those of the optimum value to realize Green Driving utilized the characteristics of HEV (Fig. 11).

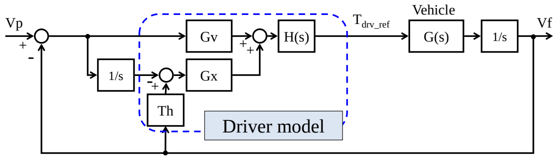

Figure10: Driver model

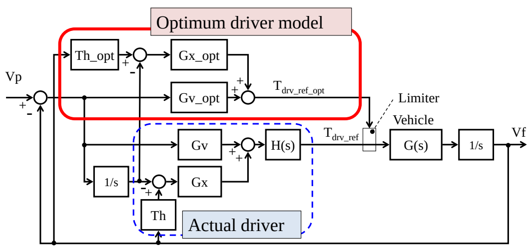

Figure11: Preceding-vehicle follow-up model with control for Green Driving assistance

Table1: Variable list of block diagram

Symbol	Definition	Unit
Gx	Rerative distance gain	N
Gv	Rerative velocity gain	N/s
Th	Desired time headway	ms
s	Laplace operator	-
H(s)	Driver characteristics	-
G(s)	Vehicle acceleration characteristics	-
Vp	Preceding vehicle velocity	m/s
Vf	Following vehicle velocity	m/s
Tdrv_ref	Driver request traction force	Nm

5.3 Design of cut-off frequency

The author designed the target value of the “cut-off frequency of the vehicle speed” for the optimum driver model through an actual vehicle test. There are two requirements for design of the cut-off frequency. One is that the optimum driver model can reduce the frequency component of the vehicle speed unnecessary for “preceding-vehicle follow-up”. The other is that the optimum driver model can output the driver operation without causing drivability stress to the driver.

First, in order to clarify the threshold level of the cut-off frequency which satisfies the two requirements, the author conducted an actual vehicle test. In the test, the following vehicle followed the "preceding vehicle driving according to Vp which repeating acceleration / deceleration of 0.02 Hz to 0.2 Hz" (Fig. 12). The author changed the cut-off frequency; Gv = 1000, Th = 2000 as fixed value, Gx as variable, which are driver characteristics parameters. Gx represents responsiveness to inter-vehicle distance, and responsiveness improves when Gx is large. Then, the author examined Gx, which test driver feels that the cut-off frequency satisfies the two requirements. As a result, the author decided to set the driver characteristic parameter in the case of Gx = 1000 to the cut-off frequency threshold level.

Second, the author designed the cut-off frequency through analysis of "frequency response" of "following vehicle speed" relative to "preceding vehicle speed" in the test result. Then, the author decided to set 0.07 Hz as the target value, which is the cut-off frequency of the optimum driver model under Gx = 1000 (Fig. 12).

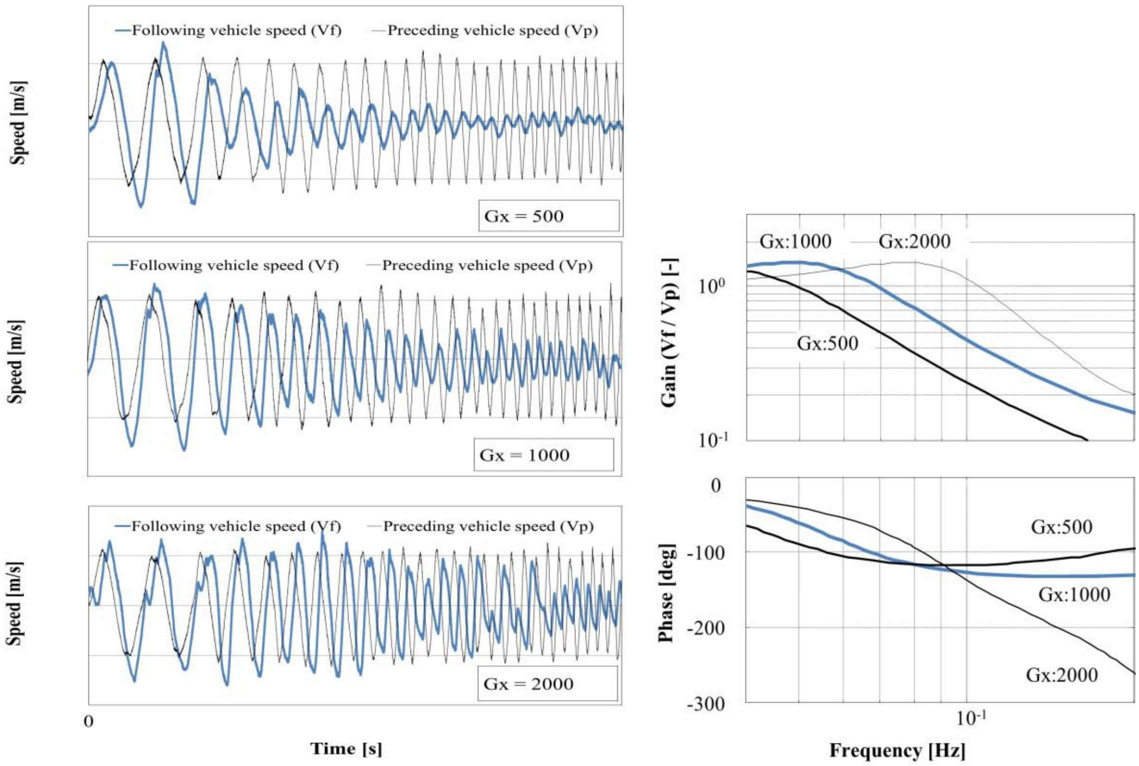

Figure12: Test data of vehicle speed

5.4 Identification of optimum driver characteristic parameters

The author matched the driver characteristic parameter of the optimum driver model as "cut-off frequency at the target value of 0.07 Hz".

Equation 1 shows the transfer function of the base driver model. Fig. 13 shows the tendency of the frequency response of “the following vehicle speed on the preceding vehicle speed” when Gx and Gv are changed. When Gx is large, the vehicle speed fluctuation increases according to the "change in inter-vehicle distance". When Gv is small, the vehicle speed fluctuation increases according to the "change in relative speed".

$$\frac{V_f(s)}{V_p(s)} = \frac{G(s)H(s)(G_v s + G_x)}{s^2 + (G_x T_h + G_v)G(s)H(s)s + G_x G(s)H(s)} \tag{1}$$

The author matched the driver characteristic parameters that the “cut-off frequency of the vehicle speed” is 0.07 Hz through a driving simulator. Table 2 shows the results.

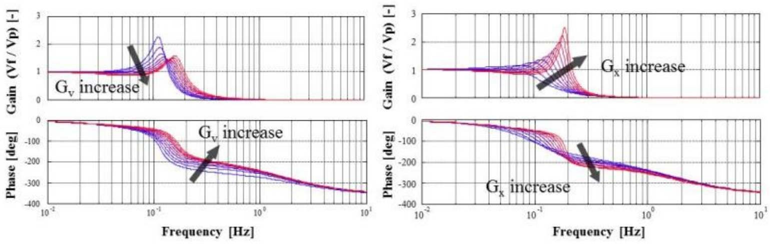

Figure13: Behavior of frequency response to gain variation

Table 2: Parameter of optimum driver characteristics

Th	Gx	Gv
1500	500	2000
2000	1000	1000
3000	2000	500

5.5 Installation of Green Driving Assistance System

The author established the new Green Driving Assistance System by installing the optimum driver model in the power management control in an on-board system. “Power management control" controls the output torque to engine and motor, by inputting the information of driver operation, vehicle and so on.

The optimum driver model should be installed so that the target value calculated by the optimum driver model can assist the driver's operation. One of the functions of power management control is to calculate the demanded torque value to the engine and the motor based on various kind of information including the driver operation.

Therefore, to install the optimum driver model in power management control is an appropriate method to realize the new system.

5.6 Verification of cut-off frequency of Green Driving Assistance System

The author verified the “cut-off frequency of the vehicle speed” of the new Green Driving Assistance System through an actual vehicle test. In the test, the "following vehicle" followed the "preceding vehicle driving according to Vp which repeating acceleration / deceleration" (Fig. 14). The driver characteristic parameters are Gx = 1000, Gv = 1000, and Th = 2000.

The author converted the time series data of the vehicle speed acquired during the test into PSD and analysed the PSD. The result showed that the new system reduced the frequency component of the vehicle speed of 0.07 Hz or larger (Fig. 14).

From the results above, the author concluded that the new system can assist driver's operations so that the driver keep the “cut-off frequency of the vehicle speed” 0.07 Hz.

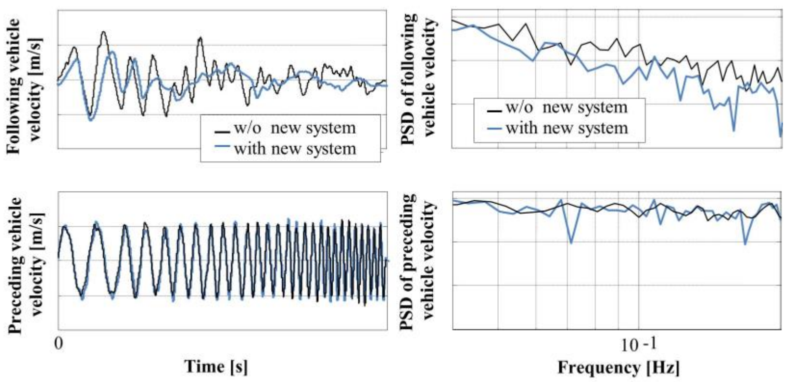

Figure14: Behavior of frequency response to gain variation

6 Verification and result

The author ran MATLAB simulation and conducted actual vehicle test to verify the fuel efficiency improvement effect of HEVs by the new Green Driving Assistance System.

6.1 Simulation with MATLAB

The author confirmed the effect, focusing on the difference between acceleration energy and regenerative energy with and without the new system through MATLAB simulation.

6.1.1 Method

The simulation method is as follows. First, in order to acquire acceleration energy data for analysis, the following vehicle followed the preceding vehicle which drove according to Vp in Fig. 15, with and without the new system. Second, in order to acquire regenerative energy data, the following vehicle followed the preceding vehicle which drove according to Vp in Fig. 16, with and without the new system.

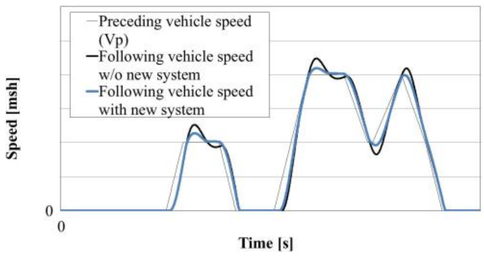

Figure15: Simulation result
during acceleration and steady state

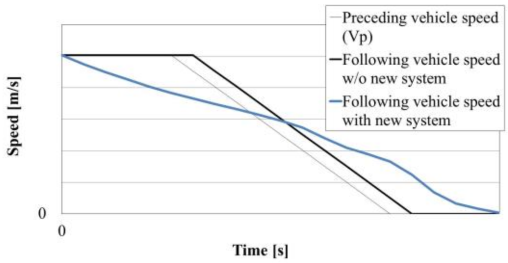

Figure16: Simulation result
during deceleration

6.1.2 Result

The author analysed the driving data acquired through the simulation, focusing on energy. The results showed that the new system reduced the acceleration energy and increased the regenerative energy. At the same time, the frequency of fluctuation of the vehicle speed reduced.

The conclusion above is led from two below findings. First, with the new system, the acceleration energy is 9.9% less than without the new system (Fig. 15). This result shows that the driver's accelerator operation was appropriately assisted by the new system. Second, with the new system, the regenerative energy is 35.1% higher than that without the new system (Fig. 16). This result shows that the driver's brake operation was appropriately assisted by the new system.

6.2 Actual vehicle test

The author focused on differences in fuel efficiency, acceleration energy, and regenerative energy with and without the new system through actual vehicle tests and confirmed the effect.

6.2.1 Method

The method of actual vehicle test is as follows. The following vehicle that the test drivers drove followed the preceding vehicle which drove according to Vp of Fig.17 with and without the new system.

In the test, each test driver drove without the new system and with new system. There were five test drivers and the test vehicle is HEV which is a heavy-duty vehicle. In the test, the author requested two things to the test drivers. One is to set the inter-vehicle distance with your own sense of everyday, and the other is to avoid the inter-vehicle distance become too long.

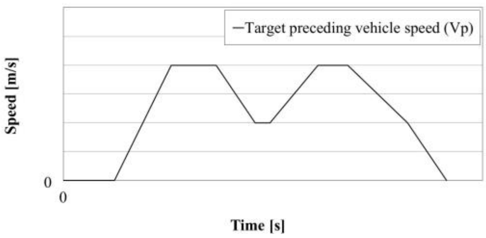

Figure17: Target preceding vehicle speed

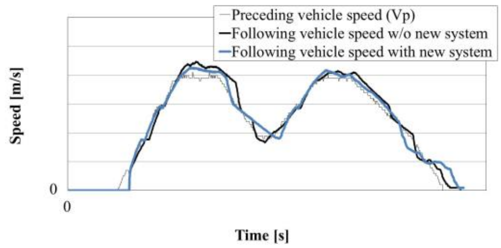

Figure18: Driving data of actual vehicle test

6.2.2 Result

The author analysed the driving data acquired during the actual vehicle test, focusing on fuel efficiency. The result shows that the new system reduces the frequency of fluctuation of the vehicle speed. At the same time, the new system improves fuel efficiency.

First, with the new system, the average fuel efficiency is 5.8% less than that of without the new system case (Fig. 19). Second, with the new system, the average acceleration energy is 6.8% less than that of without the new system case (Fig. 20). This result shows that the driver's accelerator operation was appropriately assisted by the new system. Finally, with the new system, the average regenerative energy is 15.8% higher than that of without the new system case (Fig. 20). This result shows that the driver's brake operation was appropriately assisted by the new system.

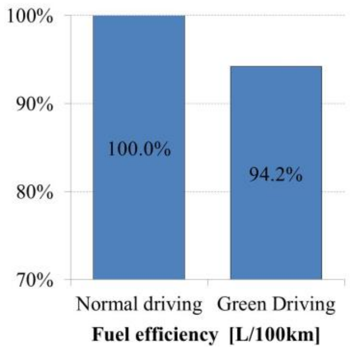

Figure19: Fuel efficiency

of actual vehicle test

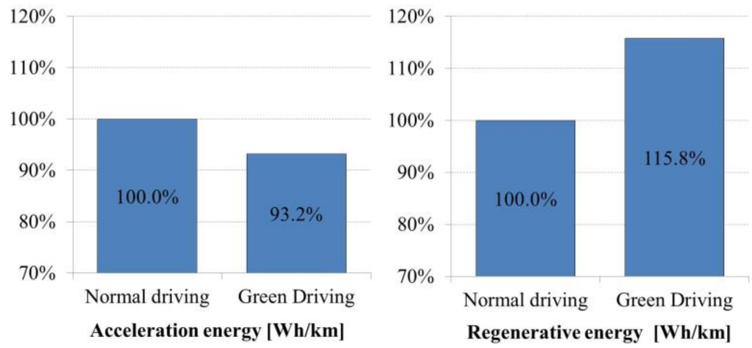

Figure20: Vehicle energy

of actual vehicle test

7 Conclusion

The author developed the new Green Driving Assistance System to achieve further improvement of the fuel efficiency of HEVs. The new system assists the driver's operation to have responsiveness without causing drivability stress and to reduce “high frequency component of the vehicle speed” in a car-following situation.

First, the author showed the fuel efficiency difference between Green Driving and normal driving and identified the factor of its difference. The author analysed driving data acquired through an actual vehicle test and the fuel efficiency of Green Driving utilized the characteristics of HEVs was 12.8% less than that of normal driving. In addition, the author concluded that the factor of fuel efficiency difference is to keep the “high frequency component of the vehicle speed” of Green Driving less than that of the normal driving.

Secondly, the author set assisting the driver's operation to have responsiveness without causing drivability stress and reducing the “high frequency component of the vehicle speed” in a car-following situation as the goal of the new system development.

Thirdly, the author designed the new system by installing an optimum driver model for Green Driving utilized the characteristics of HEVs in a “preceding-vehicle follow-up” model. The author decided to set 0.07 Hz as the target value of the “cut-off frequency of the vehicle speed” for the optimum driver model through an actual vehicle test. The author showed that the new system can assist driver's operations so that the driver keep the “cut-off frequency of the vehicle speed” 0.07 Hz through an actual vehicle test.

Finally, the author ran MATLAB simulation and conducted actual vehicle test to verify the fuel efficiency improvement effect of HEVs by the new system. As a result, the author showed that with the new system, the average fuel efficiency is 5.8% less than that of without the new system case.

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