

Energy Efficiency Improvements for a Series Hybrid Vehicle

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ABSTRACT

A system was developed for a series hybrid electric vehicle that is characterized by mechanically separating the engine and axle to thereby enable operation in the optimum electric generation range. This system was developed to vastly improve fuel economy without sacrificing vehicle dynamic performance.

The study focused on real-time generating without surplus or deficit in accordance with motor power to improve energy transfer efficiency and decrease the size and weight of the energy storage unit. At the same time, generating efficiency was improved by operating the engine with a minimum Brake Specific Fuel Consumption (BSFC). The system was tested on a 1 500 kg equivalent inertia weight class vehicle whereby it was verified that a 94% fuel economy was achieved in comparison to gasoline-powered vehicles in the same class, while no sacrifices were made to dynamic performance.

1. Introduction

With increased interest in global environmental issues, demand has further increased for technology to reduce automobile fuel consumption. Attention is currently focused on reducing vehicle body size and weight, and efforts are also underway to develop engine technologies to improve fuel efficiency such as direct injection gasoline and diesel engines. In addition, hybrid systems are attracting attention as a total vehicle technology, with some hybrid vehicles having already been released to the market.⁽¹⁾⁽²⁾

This study focused in particular on the series hybrid electric vehicle (hereafter “SHEV”) characterized by a mechanically separate engine and axle enabling operation in the optimum electric generation range. Further, we attempted to vastly improve fuel efficiency for a SHEV without sacrificing vehicle dynamic performance compared to a gasoline fueled vehicle of the same equivalent inertia weight class.

2. Aim of This Study

Most conventional SHEV use an energy storage (hereafter “E/S”) system in which a compact generator is mounted on an electric vehicle.⁽³⁾ In these systems, the motor power is provided by the E/S, and the discharged energy is replenished by the generator. However, the following problems make it difficult to improve fuel efficiency.

- (1) The E/S weight and size increase in order to guarantee motor power with the E/S.
- (2) The E/S charge/discharge loss degrades energy transfer efficiency.

In this study, the authors thought that if real-time generating could be performed without surplus or deficit in accordance with the motor power, the E/S size and weight

could be reduced and at the same time the charge/discharge loss could also be greatly reduced and the energy transfer efficiency improved, thus overcoming these problems. It was thought that by utilizing the above-mentioned feature of the SHEV, the engine could be constantly operated in the high efficiency range even if the generation level was varied, thus yielding vast fuel efficiency improvement effects compared to the same class of gasoline fueled vehicles.

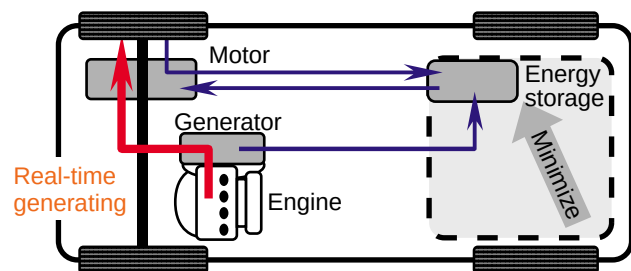


Fig.1 Real-time generating and minimized energy storage

Next, the effect of real-time generating on transfer efficiency within the energy transfer system shown in Fig.2 is explained. Here, η_{GEN} is the generator efficiency, $\eta_{\text{E/S}}$ is the E/S charge/discharge efficiency, and η_{MOT} is the motor efficiency.

The energy transfer efficiency when the conventional generating method and the real-time generating method are applied to this energy transfer system can be expressed by the following equations.

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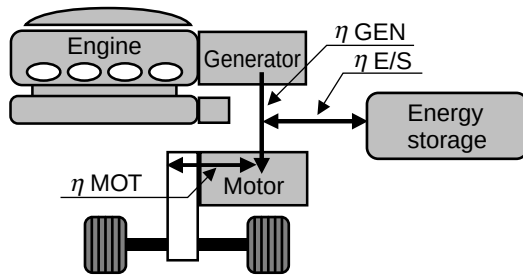


Fig.2 Energy transfer efficiency

Conventional generating method:

$$\text{Energy transfer efficiency} = \eta_{GEN} \times \eta_{E/S} (\text{Charge}) \times \eta_{E/S} (\text{Discharge}) \times \eta_{MOT} \quad (1)$$

Real-time generating method:

$$\text{Energy transfer efficiency} = \eta_{GEN} \times \eta_{MOT} \quad (2)$$

When calculated assuming each of the efficiencies in equations (1) and (2) above are 90%, the energy transfer efficiency for real-time generating is 81% while it is 65% for the conventional method.

3. Control System

3.1. Control System Configuration

Fig.3 shows the overall control system configuration.

The system can be broadly divided into the following three control units.

- (1) Generating control block
- (2) Brake Specific Fuel Consumption (BSFC) bottom trace controller
- (3) Engine, generator and motor controllers

The generating control block is comprised of the real-time generating controller, which forms the base, and the interval power controller, which turns the generator on and off according to the E/S state of charge (hereafter "SOC") when the generator power requirement is low. This block determines the target motor torque and generator power

requirement based on the acceleration pedal angle and the vehicle speed.

The BSFC bottom trace controller determines the target generator power and the throttle angle to minimize the BSFC based on the generator power requirement determined by the generating control block.

The motor, generator and engine controllers control their respective control subjects in accordance with the target torque, target generator power and throttle angle determined above.

The generating control block and BSFC bottom trace controller characteristic of this control system are described in the following sections.

3.2. Real-time Generating Control

Fig.4 shows the real-time generating controller structure outline.

This controller determines the basic generator power by estimating the electric power required to drive the motor from the target motor torque and the vehicle speed, and then adding other power consumption. Generating action can be started before actual power consumption starts by estimating the power requirement with a feed-forward system. This improves generating responsiveness, and makes it possible to reduce temporary discharge from the E/S even when the motor power changes suddenly, thereby achieving energy management to minimize charge/discharge loss.

In addition, the generator power requirement is

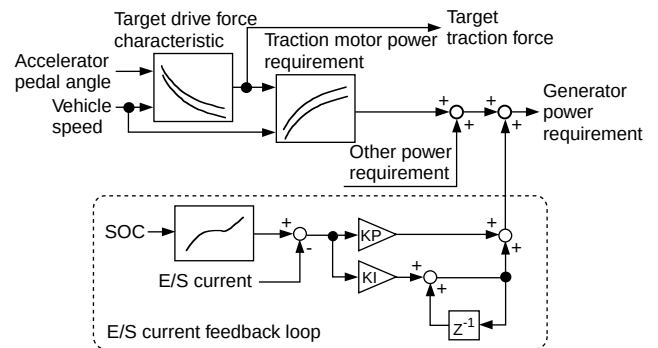


Fig.4 Real time generating control structure

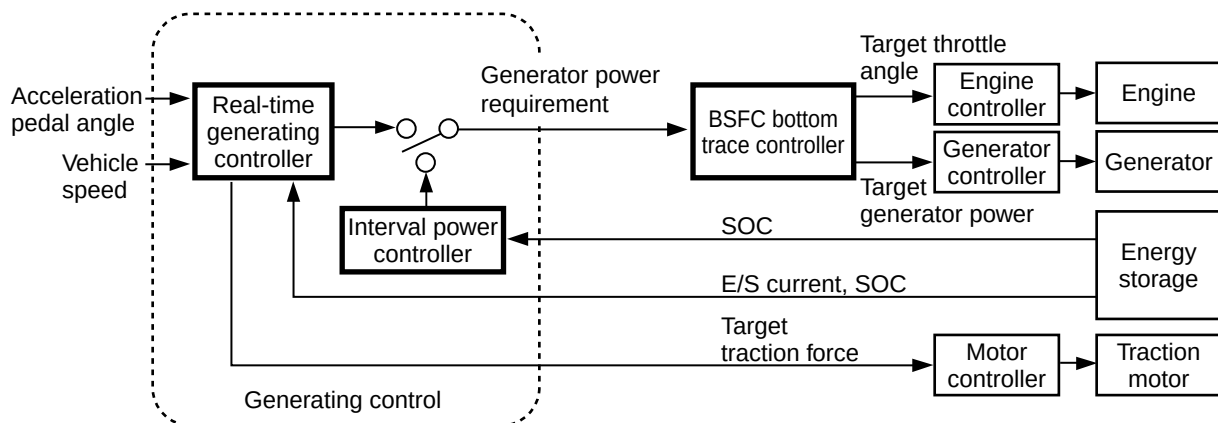


Fig.3 System block diagram

determined by adding a SOC feedback system to the above-mentioned feed-forward system and correcting the basic generator power according to the SOC. This prevents E/S over-charge and discharge caused by the discrepancy between the actual power consumption and estimated power due to temporary discharge from the E/S generated during over-response, recovery of deceleration energy, changes in motor efficiency and other factors. This makes it possible to maintain the SOC at a fairly constant level.

3.3. BSFC Bottom Trace Control

The generating efficiency is the product of generator efficiency and engine efficiency. However, since engine efficiency is dominant over almost the entire operating range, the degree to which engine efficiency can be increased during generation is critical. Utilizing the SHEV feature whereby the engine revolutions are not dependent on the vehicle speed, the required generator power can be generated above the BSFC bottom line shown in Fig.5.⁽⁴⁾⁽⁵⁾

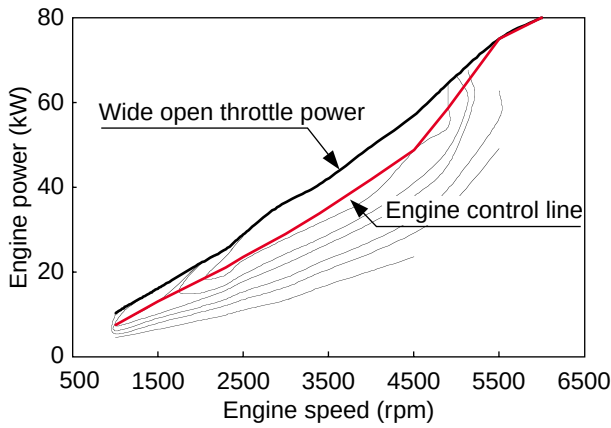


Fig.5 BSFC characteristic

Fig.6 shows the BSFC bottom trace control structure outline. The combination of the engine revolutions and the throttle angle that minimizes the BSFC with respect to the generator power requirement determined by the generating control block is calculated as the target. The actual engine revolutions are fed back to control the generation of a generator linked directly to the engine so that the engine follows the target revolutions, and the engine output is adjusted by controlling the throttle angle. This makes it possible to realize superior response characteristics, even when a particularly rapid generating response is required,

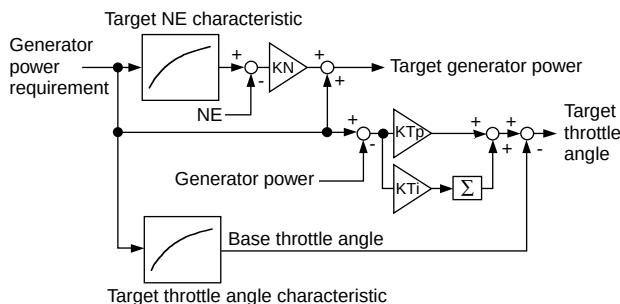


Fig.6 BSFC bottom trace control structure

by feeding back the actual revolutions and actively reducing the engine load to increase the engine revolutions.

3.4. Interval Power Control

As noted thus far, high efficiency generating which follows the motor power can essentially be performed by combining real-time generating control and BSFC bottom trace control. However, Fig.5 shows that the BSFC degrades in the low engine output range. Therefore, when the required motor power is small, the generator is controlled at intervals so that the low output range with poor BSFC is not used. As shown in Fig.7, during interval power control, generating is stopped and power is supplied with only the E/S when the SOC is at the upper limit or higher, and generating is performed at a level that exceeds the motor power when the SOC falls below the lower limit. In addition, the engine is stopped when not generating in order to reduce wasteful fuel consumption due to idling.

In this manner, interval power control works to prevent drops in generating efficiency. However, it also produces E/S charge/discharge loss, so the interval power control range must be determined according to the balance of these two factors.

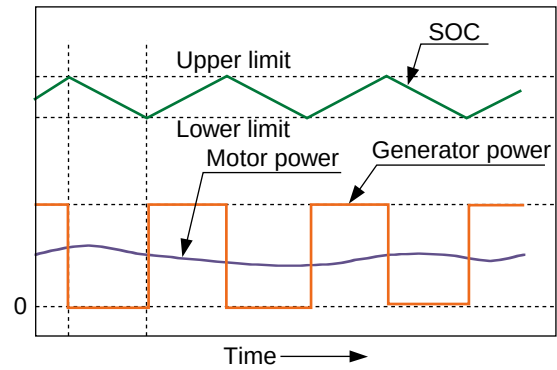


Fig.7 Interval power control

3.5. Recovery of Deceleration Energy

The motor regeneration level was set according to vehicle speed as shown in Fig.8 in order to avoid giving an unnatural feel to the driver when decelerating. In addition, the motor regeneration level is increased during braking to further increase recovery of deceleration energy.

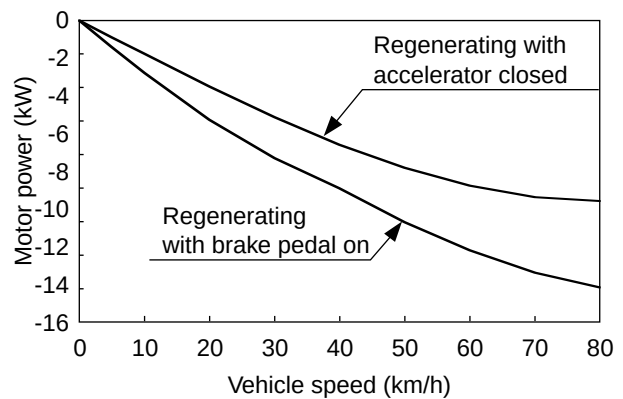


Fig.8 Regenerative braking power curve

4. Verification with an Actual Vehicle

4.1. Prototype Vehicle Specifications

The prototype vehicle was a 1500 kg equivalent inertia weight class, and Table 1 shows the major specifications.

Table 1 Major specification

Model		
Vehicle	Inertia weight (kg)	1500
	Maximum velocity (km/h)	130
Motor	Type	DC brushless
	Maximum power (kW)	73.5
	Maximum torque (N·m)	275
Engine	Type	Water-cooled gasoline engine
	Displacement (cm ³)	1493
	Valve train	SOHC VTEC
	Maximum power (kW/rpm)	95.6/7000
	Maximum torque (N·m/rpm)	139.3/5300
Generator	Type	DC brushless
	Maximum power (kW)	80
	Maximum torque (N·m)	130
Energy storage	Maximum power (kW)	30
	Energy capacity (Ah)	5
	Weight (kg)	60

In addition, Fig.9 shows the maximum motor power line for the prototype vehicle and the maximum traction line for a gasoline-fueled 4AT vehicle of the same inertia weight class. In order to achieve the same dynamic performance as the comparison vehicle, the motor maximum power was set at 73.5 kW in order to satisfy the traction characteristics. The maximum power generation was set at 80 kW in consideration of efficiency so that the entire motor output could be provided during real-time generation. Regarding the E/S weight, an 80 kW/5 Ah E/S is required to guarantee maximum motor power for a conventional SHEV. Therefore, assuming an output density of 500 W/kg, a 160 kg E/S must be mounted. However, with this system the E/S need only

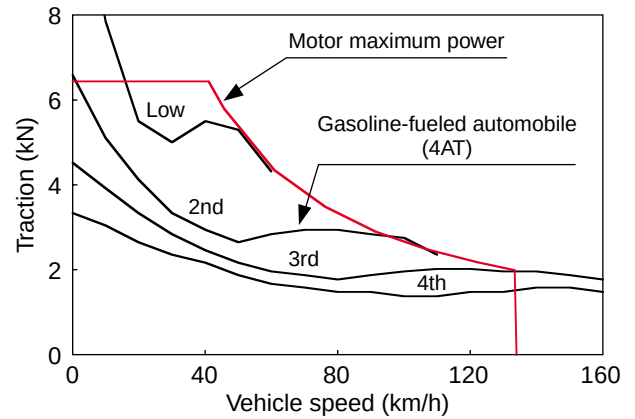


Fig.9 Drive force curve

guarantee the generating response lag during acceleration and the recovery of deceleration energy. Thus a 30 kW/5 Ah and 60 kg E/S can be mounted, thus realizing a weight reduction of 62.5%.

4.2. Control Algorithm

Fig.10 shows the transitions in motor power, generator power and SOC in the 10-15 mode utilized in order to verify the behavior of the entire control system. Power is generated during acceleration when the motor power increases, and power generation is stopped when the generator power requirement is low such as during cruising or idling, or when recovering deceleration energy. The 10-15 mode requires little motor power overall, so generating is frequently stopped by interval power control and the SOC decreases when generating is stopped. However, the consumed energy is replenished by the recovery of deceleration energy and by SOC feedback during real-time generating control, so the SOC is maintained at a fairly constant value.

Fig.11 shows the transition from interval power control to real-time generating control in Fig.10, particularly during acceleration. When the motor power reaches the prescribed value of 10 kW, the engine starts and generating starts. When generating starts, generating is performed at the motor power or higher in order to replenish the energy consumed by interval driving and the generating response lag, enabling the recovery of the SOC. In addition, the generator power

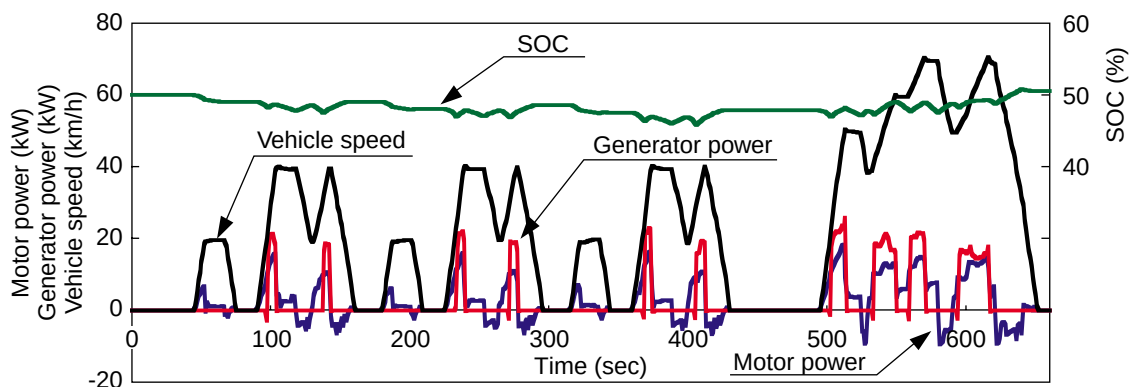


Fig.10 System behavior (10-15 mode)

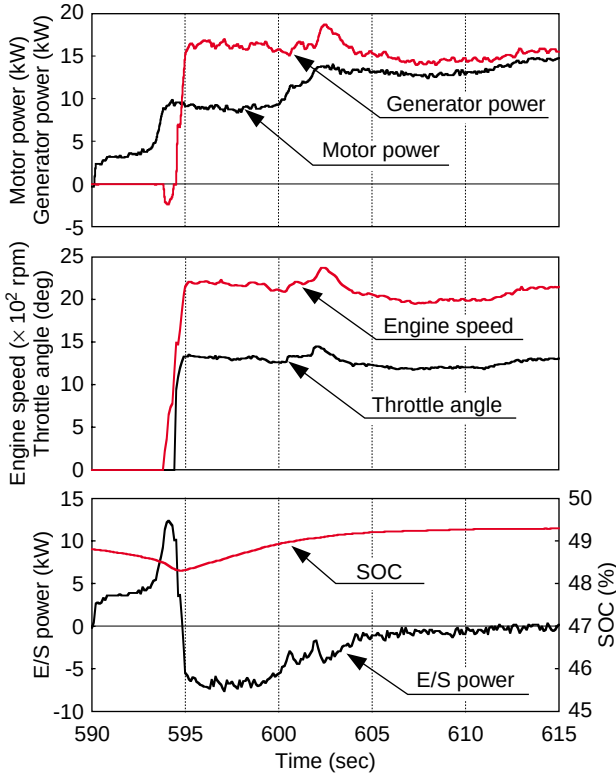


Fig.11 Generating behavior

and the engine power are about the same. Therefore, the engine driving point at this time is approximately 15 kW, 2000 rpm, which matches with the engine minimum BSFC point shown in Fig.5.

4.3. Efficiency

Figs.12 and 13 respectively show the energy transfer efficiency and engine driving range in the 10-15 mode. These graphs show that the energy transfer efficiency reaches approximately 80% of the initial target by performing real-time generating control, and the engine driving range is also on the BSFC bottom line due to the performance of BSFC bottom trace control.

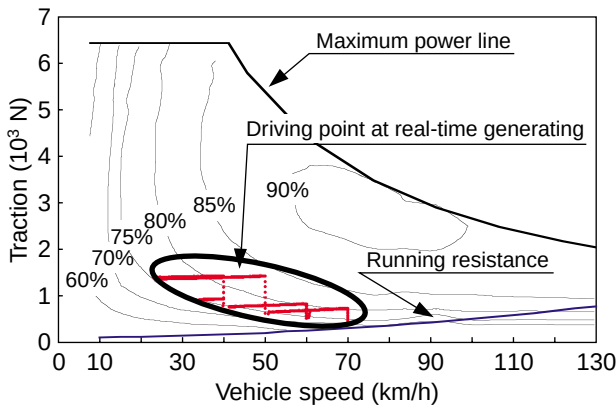
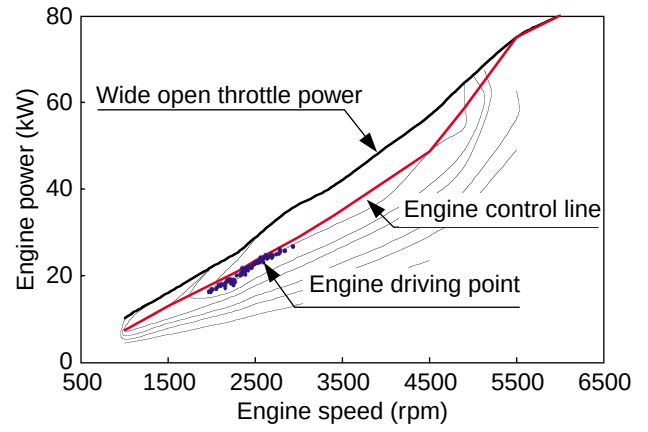

 Fig.12 Transfer efficiency characteristic ($\eta_{MOT} \times \eta_{GEN}$)


Fig.13 BSFC characteristic and engine driving point

4.4. Fuel Efficiency

Fig.14 shows the fuel efficiency improvement effects of each control method in the 10-15 mode. The mode fuel efficiency ultimately reached 23.3 km/L, thus confirming fuel efficiency improvement effects of 94% with respect to the comparison vehicle.

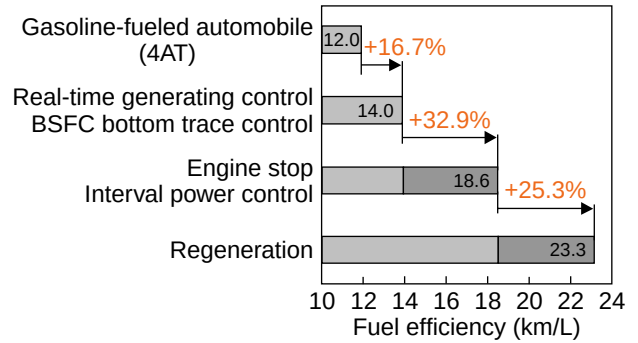


Fig.14 10-15 mode fuel efficiency

5. Conclusions

Focusing on the SHEV characteristic whereby the engine and axle are mechanically separated to facilitate operation in the optimum range of electric generation, the authors created a system that vastly improves fuel economy without sacrificing vehicle dynamic performance, and achieved the following results:

- (1) The E/S power requirement was reduced and at the same time the energy transfer efficiency was improved by performing real-time generating without surplus or deficit in accordance with the motor power. This resulted in an E/S weight reduction of 62.5% and achieved an energy transfer efficiency of 80% in the 10-15 mode.
- (2) The energy transfer efficiency was raised and generating was performed to constantly minimize the engine BSFC by real-time generating control and BSFC bottom trace control. This resulted in fuel efficiency improvement effects of 16.7% in the 10-15 mode with respect to the comparison vehicle.

- (3) Additional fuel efficiency improvement effects of 32.9% over (2) above were obtained by performing interval power control and stopping the engine in the low power range where engine efficiency is poor.
- (4) Fuel efficiency was further improved by 25.3% over (3) above by recovering deceleration energy to ultimately reach 23.3 km/l. This represents fuel efficiency improvement effects of 94.2% with respect to the comparison vehicle.

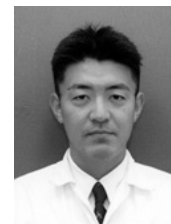
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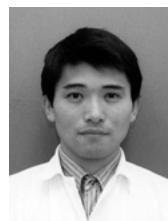
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