

Study of Small-sized Scooter Hybrid Vehicle

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ABSTRACT

In the application of hybrid technology to motorcycles, some issues including limited space for mounting a hybrid system and small regenerative energy available during deceleration are present. In order to get the maximum effect of improving fuel economy by solving these issues, we have developed a series-parallel hybrid system. This system uses a direct rear wheel driving motor that can absorb the regeneration energy during deceleration more efficiently. Additionally an idle stopping system by use of a starter AC generator, an electronically controlled fuel injection system, and an electronically controlled belt CVT (continuously variable transmission) system were adopted. Utilizing this small-sized hybrid system the experimental scooter of 50 cm³ displacement achieved an equivalent body size as the mass produced scooter with 50 cm³ engine. Furthermore, this equivalent body size was achieved while keeping a utility space under the seat. Moreover, an improvement of 60% in fuel economy under ECE 40 mode was realized.

1. Introduction

In recent years, environmental protection technology and fuel economy enhancement technology have been widely researched as a result of concerns about the global warming and the depletion of petroleum resources. Also in motorcycles, the use of three-way catalysts and fuel injection systems is being extended. The authors addressed realizing higher level of fuel economy for a motorcycle with a hybrid system⁽¹⁾, similar to the ones used on some automobiles. A series-parallel hybrid system using a direct rear wheel driving motor was developed for a scooter with 50 cm³ of displacement, which is the smallest displacement available in a commercial production motorcycle. As a result, a 60% increase in fuel economy was obtained in ECE40 mode. This paper describes the overview of the study.

2. Issues and Goals

The main issues related to the application of hybrid technology to lightweight and compact motorcycles are as follows.

- The available regenerative energy during deceleration is small.
- The available space for installation of a hybrid system is limited.

A 50 cm³ scooter was selected for research because it seemed challenging to address the above issues due to its small vehicle body and low vehicle mass. A fuel economy enhancement target of at least 50% in the ECE40 mode was set.

The major goals of the research are as follows:

- (1) Achieving the world's highest fuel economy for a scooter with a 50 cm³ engine and a belt type continuously variable transmission (CVT).
- (2) Achieving the same drivability as that of the base vehicle.

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- (3) Achieving the same utility space under the seat as that of the base vehicle.
- (4) Achieving the same body size as that of the base vehicle.

3. Examination of Hybrid Systems

Hybrid systems consist of the following three types:

- (1) Series-hybrid system
A system in which the engine is used only as the motive power for the generator and in which the vehicle is operated by a motor.
- (2) Parallel-hybrid system
A system in which the vehicle is powered mainly by the engine and a motor is used as an auxiliary source of motive power to provide assistance during start and acceleration.
- (3) Series-parallel hybrid system
A system consisting of a combination of a series-hybrid system and a parallel-hybrid system, which operates the engine and motor according to various situations in such a way as to produce maximum efficiency.

To achieve the target fuel economy enhancement, the energy consumption of the base vehicle, the 50 cm³ scooter, was analyzed and a hybrid system was studied. Figure 1 shows the result of calculating the energy balance when the vehicle is running in ECE40 mode. The top part of Fig. 1 shows the vehicle speed in ECE40 mode, the middle part the energy balance of the base vehicle, and the bottom part the energy balance of the hybrid vehicle. In Fig. 1, the output necessary for deceleration is treated as negative output.

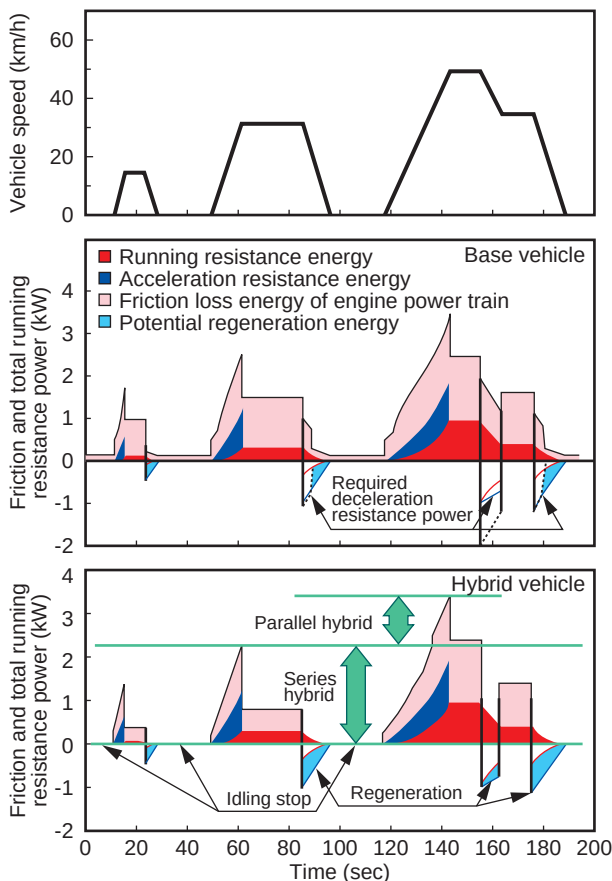


Fig. 1 Energy balance in ECE 40 mode

The remaining energy after subtracting the running resistance and the deceleration energy due to mechanical loss in the engine and the drive train from the necessary energy for deceleration, becomes the potential regeneration energy. It was found that for the base vehicle, the ratio of the mechanical loss in the engine and the drive train to the total energy necessary for running the vehicle was high, and also that this loss reduction was effective in raising the fuel economy. It was also found that the deceleration resistance due to engine friction was large compared to the resistance output necessary for deceleration, and that the potential regeneration deceleration energy could be increased by disengaging the engine from the drive train when the vehicle was decelerating. Given these facts a series-parallel hybrid system was selected as the suitable system, which can enhance fuel economy under various running conditions as indicated in the hybrid vehicle energy balance diagrams of Fig.1. In this system an idling stop, where fuel is not wastefully consumed when the vehicle is stationary is employed. Series-hybrid operation is performed in the low load running range to reduce mechanical loss in the engine and the drive train. Parallel-hybrid operation is performed in the high load running range. During deceleration the engine is disengaged from the drive train, and the deceleration energy is recovered efficiently.

4. Hybrid System Configuration

4.1. System Configuration

Figure 2 shows the configuration of the hybrid system. A two-motor hybrid system consisting of the starter-AC generator mounted on the crankshaft and the driving motor mounted on the belt-converter driven shaft was adopted. By installing a one-way clutch on the driving motor shaft, the engine is disengaged from the drive train, allowing more energy to be regenerated during deceleration. The operating revolution set point of the centrifugal starting clutch is 4 200 r/min. When the engine is running at or below 4 200 r/min, the engine is disengaged from the drive train, permitting series-hybrid operation in which the engine is used as a generator. A drive-by-wire (DBW) system is used to freely control the engine output and engine speed. The battery is a nickel-hydrogen battery, which is already being used in hybrid automobiles and features stable output characteristics that do not depend upon the charging condition. Prototype interior permanent magnet (IPM) type DC brushless motors, which have a maximum output of 1.2 kW, were used for the starter-AC generator and driving motor.

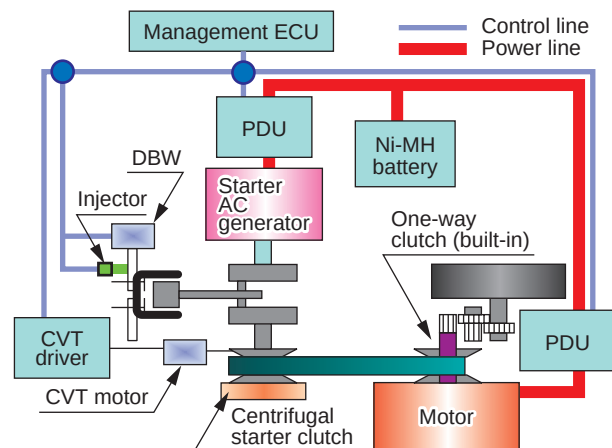


Fig. 2 Series-Parallel hybrid system

4.2. Control System

In a hybrid system it is necessary to perform cooperative control of the engine output, generator power, motor output, CVT ratio, and so forth, according to the running conditions and the condition of the battery. Therefore, the system used consisted of a management ECU, power drive unit (PDU) for the starter-AC generator, a driving motor PDU and CVT driver, and integrated control was performed by the management ECU, as shown in Fig. 2. The management ECU contains drivers for the FI and DBW. Based on the results of energy management and drive power control computations the management ECU drives the FI and DBW to control the engine output, and simultaneously assigns a target ratio and torque to the CVT driver and each PDU to control the ratio of the electronically controlled CVT as well as the output from the starter-AC generator and the driving motor.

4.3. System Installation

Figure 3 shows the components layout of the hybrid system installed on the vehicle. The battery packs were installed inside of the front cowl on both sides, and the PDUs on both sides under the seat. The layout was considered for the longitudinal and lateral mass balance so as not to affect the running stability. The PDU was mounted directly on the frame to release heat thereby eliminating the heat release fins and keeping the body compact. The FI and DBW control sections were incorporated into the management ECU. The ECU itself was miniaturized and installed rearward of the seat. As a result of these modifications the vehicle body size and the utility space under the seat were the same as those of the base vehicle.

4.4. Major Specifications

Figure 4 shows the appearance of the vehicle equipped with a hybrid system, and Table 1 shows the major specifications. Figure 5 shows the utility space under the seat.

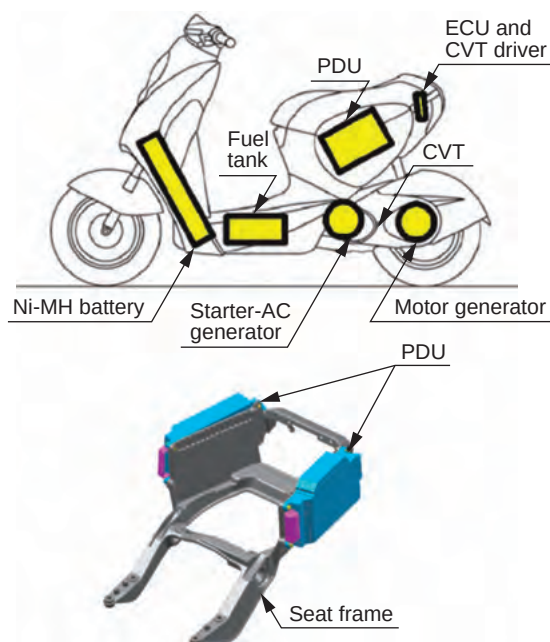


Fig. 3 Hybrid system layout

5. Fuel Economy Enhancement Technology

5.1. Series-parallel Hybrid System

Figure 6 shows the engine operation conditions when a vehicle equipped with a conventional engine is running at constant speeds of 30 km/h and 50 km/h. The brake specific fuel consumption (BSFC) at 30 km/h was larger than the BSFC at 50 km/h, indicating the fuel consumption per engine output was larger at 30 km/h. In the case of a vehicle equipped with a conventional engine, because the engine is coupled to the rear wheel via a transmission, the engine speed is determined by the vehicle speed and the gear ratio, hence it is difficult to greatly change the engine operation range. On the other hand, in the low load running range, such as when the vehicle is traveling at 30 km/h, the engine is disengaged from the drive train and series-hybrid operation is carried out, permitting the engine to be run at low speed under high load running conditions and realizing low fuel consumption (Fig. 6).

In contrast, in the high load running range, such as when the vehicle is traveling at 50 km/h, the vehicle travels in a range where the engine operation efficiency is relatively high. Therefore, the improvement level due to the use of a series-hybrid system is small. Additionally, to use a series-hybrid system it is necessary to increase the output of the motor and the generator, which imposes limitations on the mass and size of the motor and AC-generator. For these reasons it was thought that a series-parallel hybrid system that switches between series and parallel-hybrid operation during which the engine is the main motive power source would not only be effective for low fuel consumption, but also would make the system light and compact. In addition, when the vehicle is traveling under high load, the shift characteristics of the electronically controlled CVT used during parallel-hybrid operation were set to the high ratio side, and the vehicle was run at a lower engine speed to enhance the engine operation range, as shown in Fig. 6.

5.1.1. Range of switchover between series and parallel-hybrid operation

Figure 7 shows the range of series and parallel-hybrid operation. The series-hybrid operation range was set within the range of the maximum generator power, below the operating revolution of the centrifugal starting clutch and the maximum output of the driving motor. At the same time, the fuel consumption rate should be lower than that during parallel-hybrid operation in that range.



Fig. 4 Developed scooter equipped with hybrid system

Table 1 Major specifications

Items		Modified	Base
Vehicle	Overall width (mm)	630	630
	Overall height (mm)	1 010	1 010
	Wheelbase (mm)	1 190	1 190
	Seat height (mm)	710	710
	Luggage space capacity (Litter)	22	22
	Mass (kg)	93	81
	Maximum velocity (km/h)	60	60
Motor	Type	DC brushless	-
	Maximum power (kW)	1.2	-
	Maximum torque (Nm)	6	-
Starter AC generator	Type	DC brushless	-
	Maximum power (kW)	1.2	-
	Maximum torque (Nm)	6	-
Engine	Type	Water-cooled gasoline engine	Water-cooled gasoline engine
	Displacement (cm ³)	49	49
	Valve train	SOHC 4-valve	SOHC 4-valve
	Maximum power (kW/r/min)	3.5 / 8 000	3.5 / 8 000
	Maximum torque (Nm/r/min)	4.2 / 7 000	4.2 / 6 000
Battery	Type	Ni-MH	Pb
	Energy capacity (Ah)	5	6
	Voltage (V)	36	12



Fig. 5 Luggage space

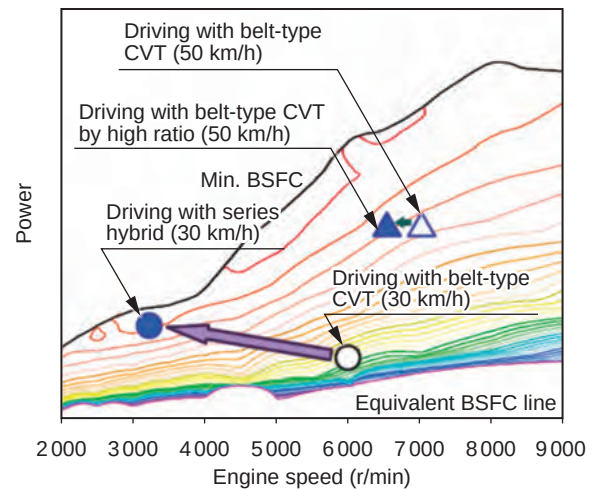


Fig. 6 Changes of engine operation conditions with series and parallel hybrid

5.1.2. Efficiency enhancement of series-hybrid operation

To enhance the energy transfer efficiency during series-hybrid operation, real-time generating control and BSFC bottom trace control were performed⁽²⁾.

Real-time generating control is a control method for reducing loss of electric charge and discharge by generating exactly the amount of electrical energy required to operate the vehicle in real time, so as to minimize charging and discharging of the battery.

BSFC bottom trace control is a control method for minimizing fuel consumption per unit generator power when generating electricity based on real-time generating control, by generating electricity along the generating BSFC bottom line (hereafter referred to as “engine control line”). The BSFC bottom line traces the engine operation points at which the BSFC becomes as small as possible with respect to the required generator power as indicated in Fig. 8.

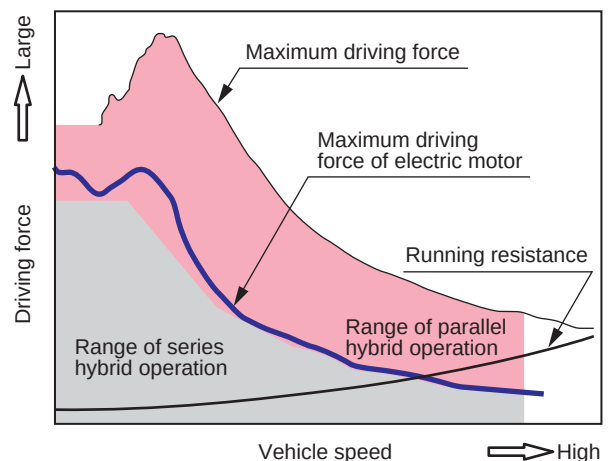


Fig. 7 Range of series or parallel hybrid driving

5.2. Recovering Deceleration Energy

A one-way clutch was used to disengage the engine and the drive train during deceleration. This allows the deceleration energy that is consumed as the engine brakes in a conventional vehicle to be recovered. Figure 9 shows the deceleration energy recovery characteristics. When the throttle is closed, the regeneration energy during deceleration is recovered.

In addition, to recover more deceleration energy the quantity of regenerative energy during braking was recovered by motor braking regeneration corresponding to the rear brake stroke.

The quantity of regenerative energy during deceleration was set to match the demand deceleration of ECE40 mode. Also, the quantity of regenerative energy during braking was set such that the upper limit was the maximum quantity of regenerative motor energy.

5.3. Other Technologies for Reducing Fuel Consumption

5.3.1. Idling stop

An effective method of reducing fuel consumption is to stop the engine whenever the vehicle comes to a stop. In this research, to reduce fuel consumption, idling stop was performed using the starter-AC generator, which is already being mass-produced.

5.3.2. Technology for reducing engine fuel consumption

Aiming at the following two points, the engine was modified, and fuel economy of the vehicle was enhanced.

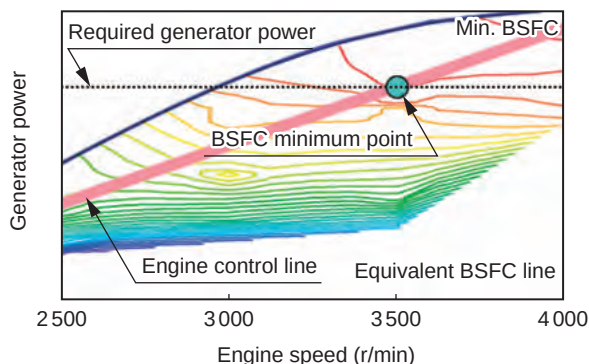


Fig. 8 Engine control line

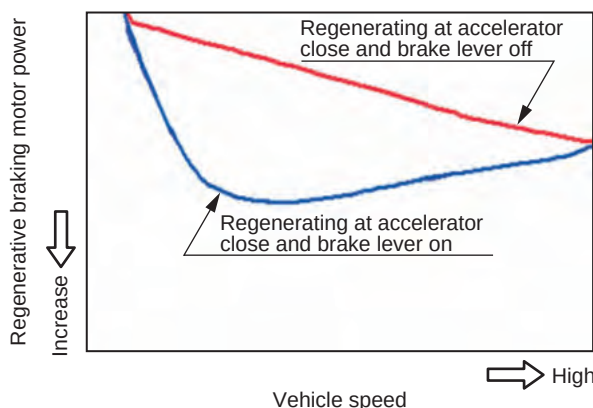


Fig. 9 Regeneration characteristics

- (1) Expansion of the stoichiometric air fuel ratio range
The acceleration compensation fuel injection quantity was reduced by means of motor assistance during acceleration. Also, an aluminum sleeve cylinder was adopted to increase the cooling performance. As a result, the stoichiometric air fuel ratio range was expanded, enabling fuel consumption to be reduced while maintaining the same exhaust gas emission potential.
- (2) Reduction of mechanical friction
As well as improved combustion, reducing mechanical friction is also important in enhancing fuel economy performance. The following technologies were used to reduce friction.
 - Ion-plating low tension piston ring
 - Molybdenum disulfide (MoS_2) shot piston⁽³⁾
 - Low friction oil seal
 - Low viscosity oil

Using a low tension piston ring is an effective method of reducing mechanical friction. However, there is a trade-off between oil consumption and blow-by gas discharge. In this research, a return hole was designed in the oil-ring groove and the dimensions were modified to reduce the tension on the oil ring.

Molybdenum disulfide shot utilizes Wonder Process Craft (WPC) treatment technology to apply high purity molybdenum disulfide to the sliding surface of the piston. This greatly reduces the sliding resistance while maintaining adequate effectiveness.

As a result of these technologies, it was possible to reduce the friction in the overall engine by at least 25% compared to that of a conventional 50 cm³ engine (Fig. 10). In addition, the engine output characteristics were changed to increase the torque at low and medium speed. As a result, the required engine speed during series-hybrid operation was lowered, enabling a reduction in friction torque and ensuring extra power.

6. Validation using Actual Vehicle

6.1. System Operation Condition

Figure 11 shows changes in system operation mode running in ECE40 mode, electric power of the motor, generator power, state of charge of the battery (hereinafter referred to as "SOC"), and the engine speed. When the vehicle is stopped, idling stop is implemented, and when the vehicle is started, EV operation is performed. During series-hybrid operation, generator power corresponding to the electric power to drive the motor is generated by real-time generating control. Also, it can be seen in Fig. 12 that the engine operation range during series-hybrid operation is on the engine control line.

When idling stop or EV operation is implemented, the SOC decreases. But because the deceleration energy and SOC feedback during real-time generating control are recovered, the SOC reverts to the startup value at the end of mode operation.

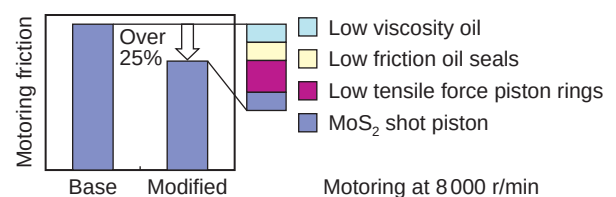


Fig. 10 Effects of engine friction reduction

6.2. ECE40 Mode Fuel Economy

Figure 13 shows the breakdown of the fuel economy enhancement effect during operation in ECE40 mode. “Parallel-hybrid” in the diagram indicates the fuel efficiency measured when the engine friction is reduced, the air-fuel ratio is maintained stoichiometrically, idling stop is implemented and parallel-hybrid operation is performed even in the low load operation range. It was found that the fuel economy was 46% higher than that of the base vehicle. “Series-parallel hybrid” in the diagram indicates the fuel efficiency measured when series-hybrid operation was performed in the low load operation range, in contrast to the abovementioned parallel-hybrid operation. The mode fuel economy for series-parallel hybrid operation reached 84 km/L, which was a 60% increase compared to that of the base vehicle.

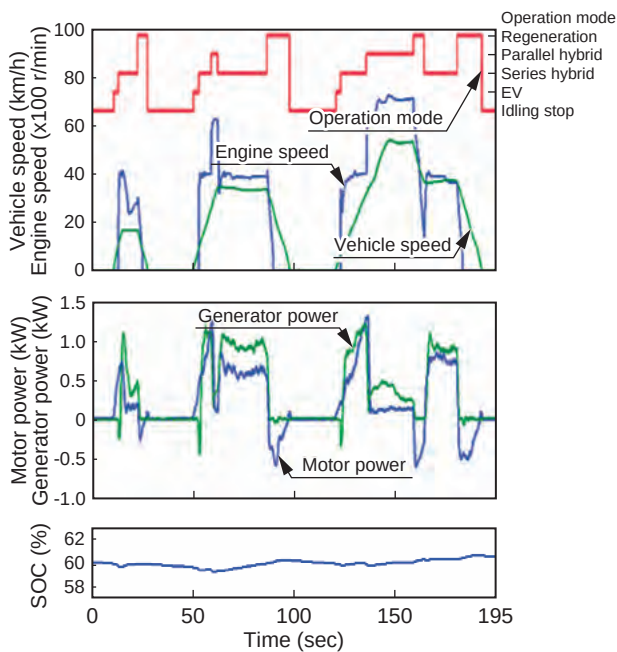


Fig. 11 System operation diagram (ECE40 mode)

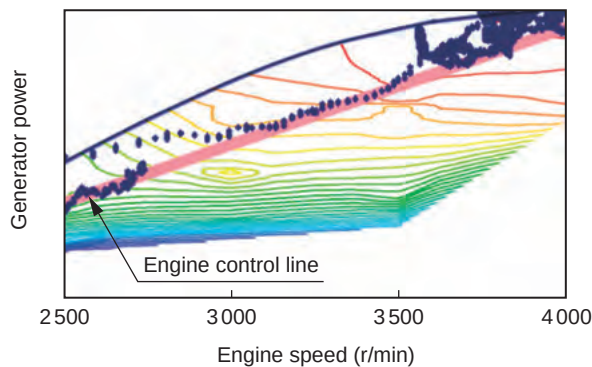


Fig. 12 ECE40 series hybrid operation region

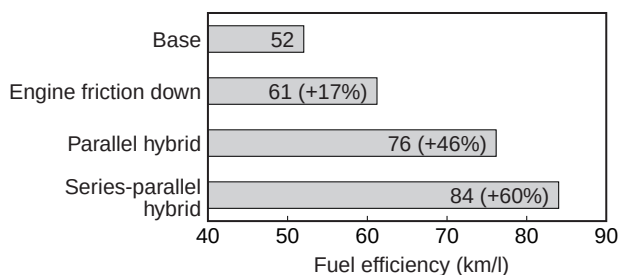


Fig. 13 ECE40 mode fuel efficiency

7. Conclusion

Tests were performed using a prototype vehicle equipped with a series-parallel hybrid system. Fuel economy enhancement was targeted for each driving condition, when the vehicle was stopped, when cruising at low and high loads, and when decelerating. The following results were obtained.

- (1) The fuel economy in ECE40 mode enhanced by 46% compared with that of the base vehicle as a result of parallel-hybrid operation, in which engine friction was reduced, the air-fuel ratio was maintained stoichiometrically, idling stop was implemented, and optimum ratio control was performed by electronically controlled CVT.
- (2) Series-hybrid operation was performed in the low load operation range, and real-time generating control and BSFC bottom trace control were performed, resulting in a fuel economy of 84 km/L. This was an additional 10.5% enhancement compared to (1) above. This is a 60% enhancement in fuel economy compared to that of the base vehicle.
- (3) The hybrid system was miniaturized and its installed position was optimized. As a result, the size of the vehicle body and the utility space under the seat were the same as those of the base vehicle.

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