No. B-14. 3. 3 A study on the power system available in the commuter transportation sector

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Abstract

The objective of this study is to reveal the proper power system for "Commuter-cars" (Ultra mini-sized vehicles for short range use), and to introduce such vehicles to urban areas to reduce CO_2 emission from vehicles.

First, a new type of the "Wheel-in-motor system" which applies a reduction gear and a high-speed DC brushless motors was designed for improving performance of present electric vehicles.

Next, a conventional EV was converted to a series hybrid vehicle with a small generator, and basic experiments were carried out on a chassis dynamometer. The range extension ratio by the hybridizing was 80 % compared to the base EV, so the suitability of series hybrid system for commuter-cars was clarified.

Therefore, a simulated series hybrid commuter-car using components of the conventional EV was set on a chassis dynamometer, and tested in transient driving patterns. Acceleration ability and energy consumption were improved by the downsizing. On the other hand, two types of series hybrid commuter-car (Charge-dependent type and Self-sustaining type) were proposed, and an optimum combination of battery and generator was considered to have sufficient running range and low environmental load.

Further, a new series hybrid system which adopted an AC inverter motor, fuel economical engine and a generation regulator was designed for a commuter car. It was examined by bench tests or calculations. As a result, both of the total energy efficiency and the performance of the system was improved remarkably in comparison with the former system mentioned above.

Finally, calculation method of life cycle CO_2 emission of the series hybrid commuter car was considered. And, the effects of introducing commuter-cars upon CO_2 reduction were estimated.

Key words Commuter-Car, Series Hybrid system, Transient Driving, CO_2 reduction

1. Introduction

In urban areas, air pollution, traffic congestion, and difficulty in parking have become urgent problems. Also, in recent years, global warming and exhaustion of natural resources have become worldwide serious issues. Remarkable increase in number of vehicles is considered to be one of the major causes of these problems. In order to cope with such problems, it is under study to develop commuter-cars in the world. Instead of ordinary cars, they are expected to be used in short range driving in urban areas.

As commuter-cars have to accelerate and decelerate frequently, electric motor traction method was picked up for them. And, series hybrid systems were thought to be more advantageous in running range in comparison with pure EV systems. Therefore, three experimental series hybrid systems were examined about performance, energy consumption and CO_2 emission in order to configure a proper power system for commuter- cars.

2. Designing of new wheel-in-motor system

The wheel-in-motor method had been already developed for EV. In order to apply this method to commuter-cars, reforming of its design were considered. Figure 1 shows the outline of the new type wheel-in-motor. The technical points are reduction gear, high-speed DC brushless motor and optimum control with new IGBT. Using this system which has torque of 64N.m and rev. speed of 8500rpm, performance of present EV can be extremely improved.

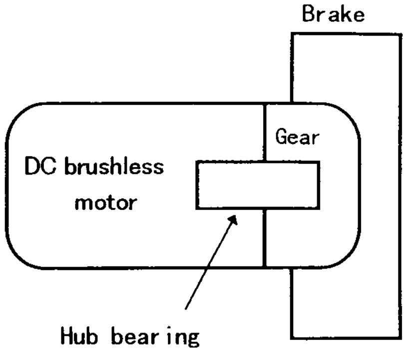

Fig.1 New wheel-in-motor

3. Chassis-dynamometer testing apparatus

Figure 2 shows the outline of the chassis-dynamometer testing apparatus. The testing vehicles were two series hybrid vehicles as shown in Table 1. The vehicle-A was converted from a conventional EV by adding a small generator and a power converter. The vehicle-B was a simulated commuter-car which uses the same motor of the vehicle-A. Two types of generators as shown in Table 2 were used, and they were running constantly. The converter input AC power from the generators, and output DC power of constant voltage.

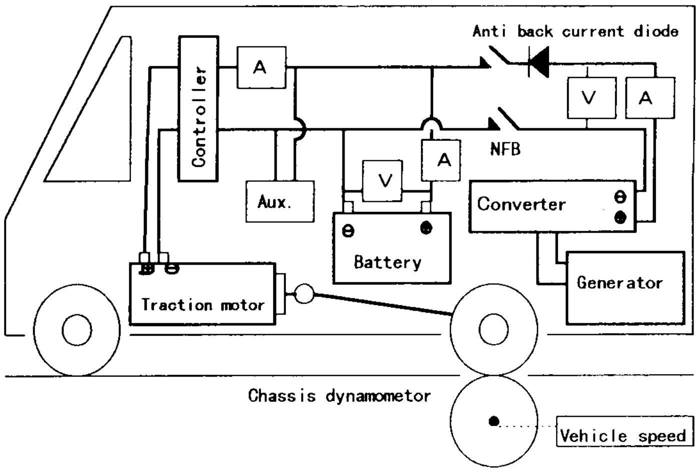

Fig.2 Chassis-dynamometer test apparatus

In this study, stored energy in batteries by commercial source is defined as "Battery energy", and supplied energy by the generator through the DC power unit is defined as "Generator energy".

4. Trial of hybridization of EV

A proper set condition of electricity supplying by the generator(a) for range- extending on the vehicle-A was considered.

The whole time average required power in 10•15-mode driving is roughly equal to the required power in cruising. However the maximum required power in the 10•15-mode driving is about six times the required power in 40 km/h cruising. Whereas the supplying capacity of the generator (a) is just 7 % of the maximum required power in 10•15- mode driving.

Table 1 Testing vehicles on chassis-dynamometer

Items		Vehicle-A	Vehicle-B (Commuter-car)
Vehicle mass (kg)		1310	700
Front projected area (m^2)		2.1	1.7
Traction motor	Type	DC Shunt	
	Max. power (kW)	20	
	Max. torque (Nm)	60	
Battery	Type	Lead - acid (Open)	
	Bass voltage (V)	120	
Gear box		5 speed	3 speed
Generator		Generator(a)	Generator(a) or Generator(b)

Table 2 Generators for testing vehicles

Items		Generator(a)	Generator(b)
Rated output power		2.1	4.3
Mass (kg)		50	100
Engine	Type	Air cooled DI diesel	
	Displacement	$230cm^3$	$412\ cm^3$
	Rev. speed	3000 (Constant)	

The output voltage of the DC power unit was set at 125V or 130V. Figure 3 shows the trajectory of battery voltage, battery power and generator power through the converter in case of the 125V setting.

In this case, the generator supplies electricity while the vehicle is in acceleration or cruising. On the other hand, in case of the 130V setting, the generator supplies not only in acceleration or cruising, but also in deceleration or stopping for charging the battery.

Figure 4 shows the correlation between the average generator output power and the average generating efficiency (from fuel energy to electric energy) of the generator(a) on the vehicle-A. In case of the130V setting, the average output power is 100% of the rated power both in cruising and 10•15-mode driving. Also the generating efficiency in case of the 130V setting is higher by 6 to 7 points than that in case of the 125V setting. Therefore, in the experimental conditions specified above, it can be said that the 130V setting is appropriate because of the available power and the generating efficiency.

The share ratio of the battery energy and the generator energy in 10•15-mode driving was approximately equal to it in 40km/h cruising. Therefore, under these two driving conditions, and the running range per one charge was measured.

Figure 5 shows the running range extension of vehicle-A in compared with those of the base EV. The extension ratio of running range obtained by hybridizing the EV is 65 % for cruising and 80 % for 10•15-mode driving.

The increased amount of mass by the generator etc. was only 5 % of the total mass of the base EV. In order to extend the running range of EV, therefore, it is better to hybridize it than to add extra battery especially in transient driving. Based on these results, it was decided to adopt a series hybrid system to an

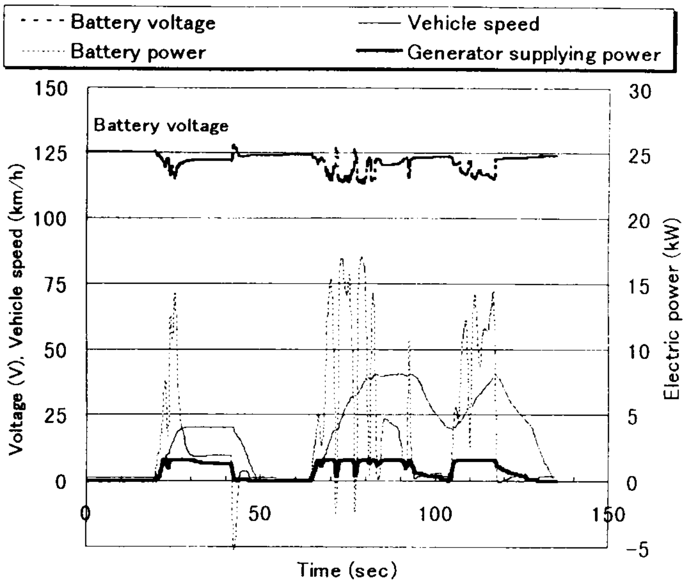

Fig. 3 Battery voltage, battery power and generator supplying power in 10mode driving (Feed setting 125V,Vehicle-A)

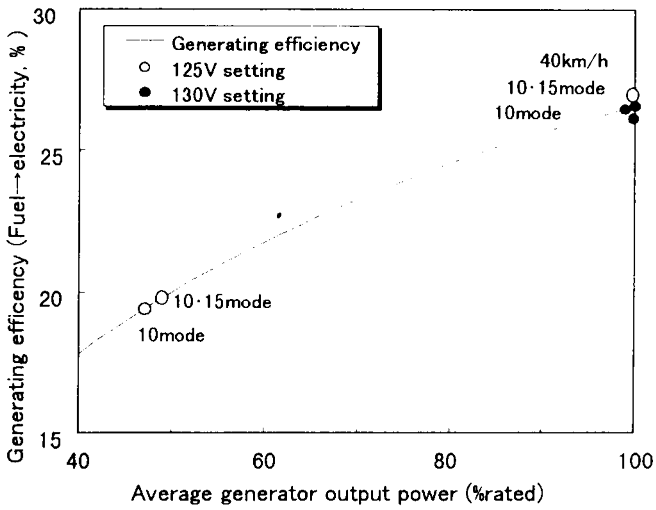

Fig. 4 Generator output power and generating efficiency (Vehicle-A)

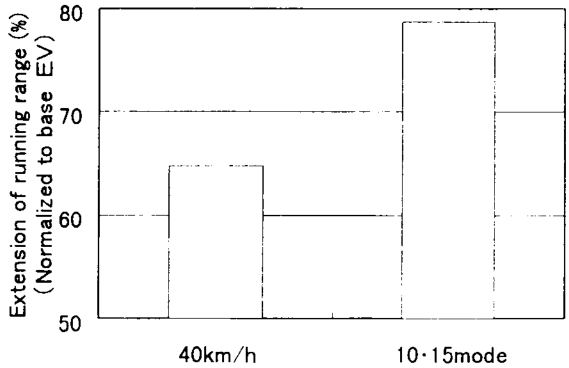

Fig. 5 Extension of running range by hybridization (Vehicle-A)

experimental commuter-car and to make indoor tests.

5. Examination on simulated series hybrid commuter-car

5.1 Starting Acceleration Performance

Figure 6 shows the average value of full acceleration from start to a speed of 40km/h of the vehicle-B. The following two gear-shift patterns were tried.

Shift-1 : Start at low gear → 2nd. gear.

Shift-2 : Start and accelerate at 2nd. gear

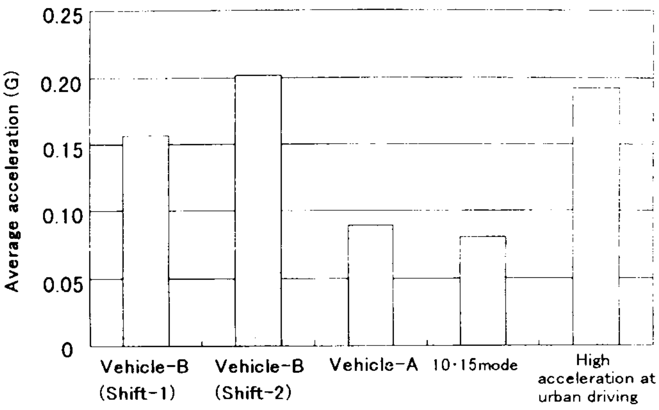

Fig. 6 Full acceleration ability (0→40km/h)

The acceleration of the vehicle-B is much higher than that of the vehicle-A. Especially, the average acceleration of the vehicle-B by the shift-2 is twice that of the vehicle-A though the reduction gear ratio is high, and such performance is sufficient for urban driving. Therefore, in order to improve starting acceleration, it is effective to reduce the inertia of electric motor and to eliminate gear-shift operation.

5.2 Required Electric Energy in Urban Driving

Table 3 shows the summary of driving patterns. The City-A represents a heavily congested traffic condition, and the City-E represents a smooth traffic condition. The City-B, the City-C and the City-D represent middle traffic conditions between the City-A and the City-E.

Figure 7 shows the required electric energy per kilometer (kWh/km) of the vehicle-B. In 40km/h cruising, the required energy for the vehicle-B is less by15 % than that for the vehicle-A. On the other hand, in transient driving, the required energy for the vehicle B is less by 20 to 30 % than that for the vehicle-A. It can be understood that the electricity saving effect by the downsizing appears remarkably in transient driving rather than in cruising. And, reduction of electric and mechanical loss is an important subject besides downsizing.

Table 3 Transient urban driving patterns

Items	10mode	10·15-mode	City-A	City-B	City-C	City-D	City-E
Max.vehicle speed (km/h)	40	70	23.7	44	49	58	69
Total average speed (km/h)	18	24	5	11	25	22	39
Running average speed(km/h)	24	33	8	18	30	36	50
Stopping time (%)	27	31	42	40	14	40	22
Start-stop frequency (time/km)	3.0	1.7	15.3	4.5	1.7	1.7	0.5

5.3 Supply and demand of electricity in series hybrid commuter-car

Figure 8 shows the average required electric power (kW) of the vehicle-B and the supplying capacity (kW) of the generators through the converter. Where the supplying capacity of the generator is less than the average required power, the battery energy is being reduced according to driving, and driving should become impossible finally.

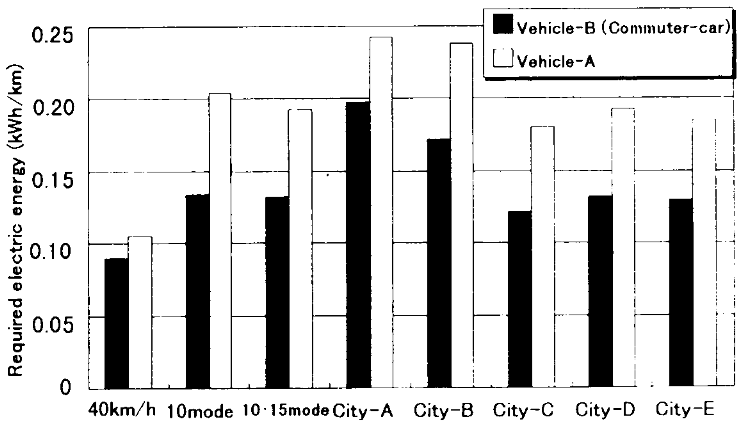

Fig.7 Required electric energy per kilometer in urban driving

To the contrary, where the supplying capacity of the generator is equal to or more than the average required power, merely the power from the generator with enough fuel can run the vehicle-B continuously.

Figure 9 shows the consumption and storage of the battery energy and the generator energy in case of mounting generator (b). All required energy can be fed only by the generator energy in almost all patterns. In the City-A and the City-B, a regulation on the generator is required because extra generator energy is accumulated gradually in the battery.

From these results mentioned above, the share between battery energy and generator energy is varied by the supplying capacity of generator. Therefore, the vehicle-B can be classified into two types. Namely the model (a) with the generator (a) is named as "Charge-dependent type" of which external charge is indispensable. Also the model (b) with the generator (b) is named as "Self-sustaining type" which can make urban driving without external charge.

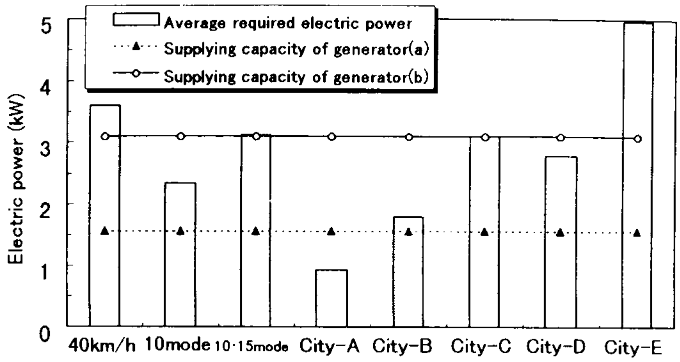

Fig.8 Average required electric power in urban driving and generator supplying capacity (Vehicle-B)

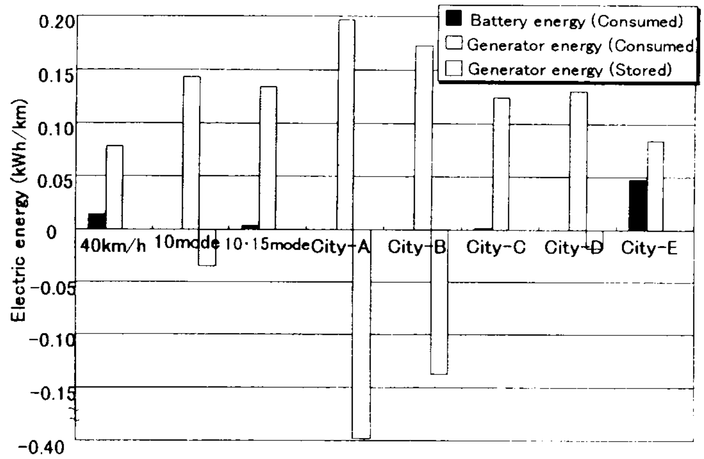

Fig.9 Use of battery energy and generator energy in urban driving (Vehicle-B with Generator(b))

5.4 Two types of series hybrid commuter-car

Combinations of the battery and generator of the vehicle-B were supposed as shown in Table 4. The sum of the battery mass and generator mass was assumed to be 300 kg. For the model (b), sub models were supposed as model (b1) to model (b3) by different fuel tank capacity. For reference, the model-EV was also supposed. Here, the distance over which these vehicles can drive only by the battery energy was defined as "Zero emission range".

From total electric energy on board, the running range of the vehicle-B is estimated as "Total energy range" by expression-1. Fuel tank capacity is a parameter of the "Total energy range". But in case of the charge-dependent type, running range can't be over the "Battery limit range" which is induced by expression-2 . With respect to running range, self-sustaining type should be far advantageous to the charge-dependent type.

Figure 10 shows the results of calculation of CO_2 emission per kilometer. In Japan, it is surmised that the higher the ratio of battery energy to the required electric energy, the less CO_2 emission [1]. As the model (a) has to use battery energy of 50 % or more for the required energy, CO_2 emission should be suppressed in comparison with the vehicle-B. Therefore, with respect to environmental

Table 4 Various model of Vehicle-B

Model	a	b1	b2	b3	EV
Generator	(a)	(b)	←	←	w/ot
Generator mass	50	100	←	←	0
Battery mass (kg)	250	200	←	←	300
Fuel tank (Liter)	5	5	10	15	0
Fuel consumption rate (liter/hr)	0.82	1.6	←	←	0

load, the charge-dependent type is thought to be desirable.

$$Total\ energy\ range\ (km) = \frac{Battery\ energy\ (kWh) + Generator\ energy(kWh)}{Required\ electlic\ energy\ per\ kilometer\ (kWh\ /\ km)}$$

(*Expression* 1)

$$Battery\ limit\ range\ (km) = \frac{Battery\ energy\ (kWh)}{Required\ energy\ per\ kilometer\ (kwh\ /\ km) - Generator\ energy\ per\ kilometer\ (kWh\ /\ km)}$$

(*Expression* 2)

5.5 Combination of battery and generator

Figure 11 shows the relationship between supplying capacity of generator and running range. The sum of battery mass and generator mass was assumed as 300 kg in any combination. Also, it was assumed that the capacity of generator was proportional to generator mass, and that the generating efficiency was independent on generator mass. The model(a) locates on the "Battery limit range" curve, and the model(b1) - (b3) locate on the "Total energy range" lines.

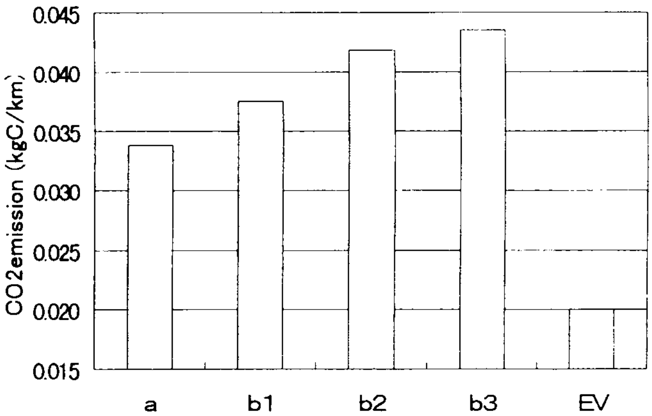

Fig.10 CO_2 emission from various model of Vehicle-B (10·15-mode)

The vertical line of 3.15kW supplying capacity is the borderline between the "Charge dependent type" and the "Self-sustaining type". Figure 11 indicates that, the "Battery limit range" curve rises remarkably near the borderline. Therefore, it is not necessary that the vehicle-B is the self-sustaining type, because the driving distance of commuter-cars will be relatively short.

As an idea, the crossing point of the "Total energy range" of 10liter fuel line with the "Battery limit range" curve was taken as the point (c), and the model (c) that corresponds to the point (c) was newly supposed. Although the supplying capacity of generator is less than 80 % of the average required power, the running range of model (c) is approx. 200 km. This value of running range is thought to be sufficient, and model (c) can be regarded as the equivalent "Self-sustaining type". On the other hand, because the model (c) necessitates battery energy for more than 20% of total required electricity, it can be assumed that environmental load can also be suppressed by adopting the model (c) in comparison with adopting the model (b2).

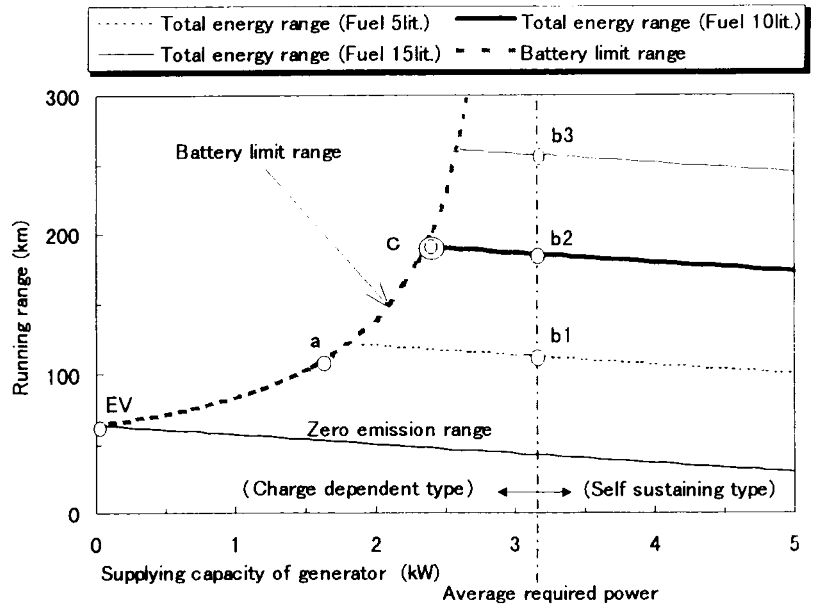

Fig.11 Relationship between supplying capacity of generator and running range (Vehicle-B, 10·15-mode)

From the results thus obtained, to optimize the combination of battery and generator, it will be proper to evaluate running range and environmental load of various supposing models such a figure.

6. Improvement of series hybrid system

In order to improve total energy efficiency of the series hybrid system which had been examined above, a new system including hi-efficient components was considered. The vehicle-C that adopted the new system was supposed as shown Table 5. The vehicle-C was examined by bench simulating tests and calculations. Figure 12 shows the bench test apparatus. The output power of traction motor was absorbed with inertia disks and a magnetic brake. By adopting an AC motor, an IGBT inverter, a hi-efficiency engine and a generation regulator etc., the total energy efficiency of the power system was improved of 40% in the 10•15-mode driving compared with the vehicle-B.

Table 5 Specification of vehicle-C

Items		Specification
Vehicle mass (kg)		700
Front projection area (m^2)		1.74
Traction motor	Type	3ΦAC Induction
	Max. power (kW)	40
	Max. torque (N•m)	125
	Controller	IGBT inverter
Transmission		Without (Fixed)
Battery	Type	Lead-acid(Sealed)
	Bass voltage (V)	240
Generator	Engine efficiency(%)	32
	Voltage (V)	3ΦAC 110~170
	Regulation	Voltage, Engine

Figure 13 shows the trajectory of the electric power of the vehicle-C in the 15mode driving. Regenerative brake effects were remarkable especially in deceleration at middle speed zone, and it saves energy consumption of 20% for total in the 10•15mode driving. On the other hand, vehicle-C can accelerate from start to 50km/h using maximum motor torque without gear-shifting. So, the vehicle-C had enough performance achieving high energy efficiency.

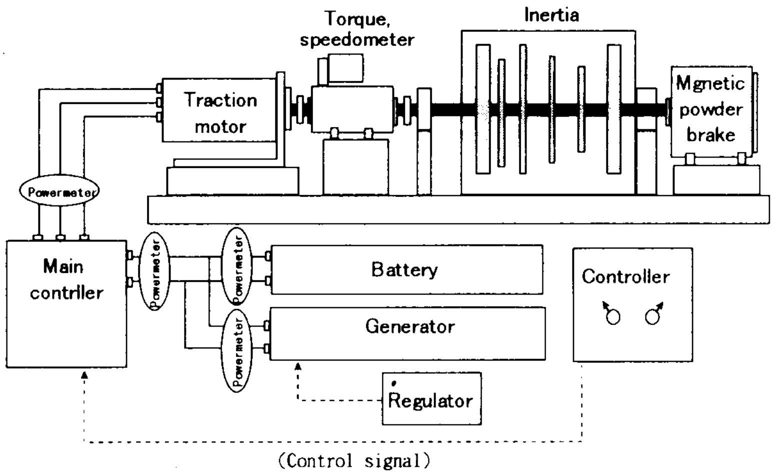

Fig. 12 Bench test apparatus for vehicle-C

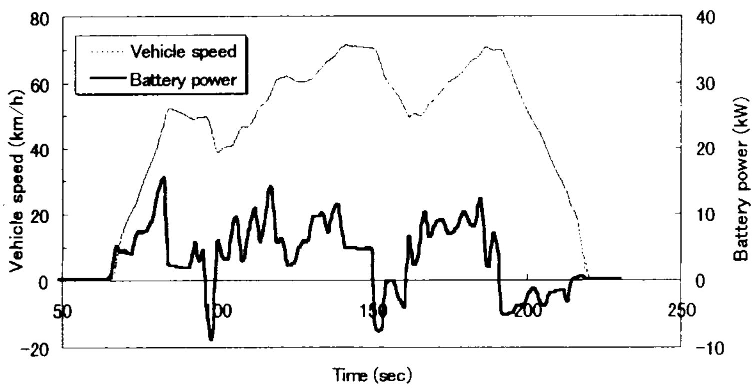

Fig. 13 Trajectory of battery power in 15mode (Vehicle-C)

7. CO_2 emission of series hybrid commuter-cars

7.1 CO_2 emission in running stage

The series hybrid commuter-cars of this study use battery energy and generator energy, then consumed energy flow from sources (Commercial electricity and petroleum fuel) is complicated. So, a method to calculate CO_2 emission in running of series hybrid vehicles was considered as following.

(1) Measure battery energy consumption and generator energy consumption on board.
(2) Induce commercial electricity consumption and fuel consumption separately.
(3) Using emission factors, calculate CO_2 emission per kilometer of a vehicle.

7.2 Effect of introducing commuter-cars upon CO_2 reduction

Targets for the replacement with commuter-cars are thought to be part of small-sized passenger cars or mini-sized passenger cars. CO_2 emission of running stage of the commuter-cars was assumed to be equal to the vehicle-C. Taking the share of CO_2 emission of running stage for life cycle CO_2 emission of ordinary cars into consideration [1], life cycle CO_2 emission of the series hybrid commuter-car was calculated. And CO_2 reduction by introducing commuter-cars was estimated. Beside simple replacement, the case in which a commuter-car would be introduced additionally to a present small-sized passenger cars and used together was also assumed. The result is shown in table 6. In case of the simple replacement of small-sized passenger cars, CO_2 reduction per vehicle and for total are the most effective. In case of the additional introducing, however reduction per vehicle is few, total reduction effect is relatively high. And, the additional introduction of commuter-cars is thought to be realized easily in comparison with the simple replacement. Entirely, introduction of series hybrid commuter-cars can be evaluated as it has high potential for CO_2 reduction.

Table 6 Effect of introducing commuter-cars upon CO2 reduction

Year	Present	2010
Total reduction	case11) -0.88Mt-C case21) -0.06Mt-C case31) -0.19Mt-C	c13) -3.52Mt-C c23) -0.44Mt-C c33) -1.00Mt-C
Reduction per vehicle	c11) -46% -0.29t-C c21) -25% -0.11t-C c31) -10% -0.06t-C	c13) -51% -0.33t-C c23) -32% -0.14t-C c33) -14% -0.09t-C
Assumption	c11) 10% of small-sized passenger cars are replaced with commuter-cars. c21) 10% of mini-sized vehicles are replaced by commuter-cars. c31) Commuter-cars are added to 10% of small-sized passenger cars, and used for 50% of running. * Battery renewal : once	c13) Small-sized passenger cars increase of 20%. 30% of them are replaced with commuter-cars. c23) Mini-sized passenger cars increase of 20%. 50% of them are replaced with commuter-cars. c33) Commuter-cars are added to 30% of small-sized passenger cars, and used for 50% of running.
	* The number of vehicles in Japan (Mar. 1995) Small-sized passenger cars : 30.8 million Mini-size passenger cars : 5.2 million * Energy share of hybrid Commuter-cars Battery energy : 50% Generator energy : 50% * Running distance 10,000km/year/vehicle * Life cycle time : 10 years	

8. Results

(1) The new type of "wheel-in-motor" which applied reduction gear, hi-speed DC brushless motor was designed for improving performance of present EV.

(2) A hybridization of a conventional EV was tried with a small generator. The running range was extended remarkably, and the suitability of series hybrid systems for commuter cars were clarified.

(3) A simulated series hybrid commuter-car was examined by indoor tests. The acceleration and energy consumption were improved according to downsizing.

(4) Series hybrid commuter-cars was classified into "Charge-dependent type" and "Self-sustaining type". A optimization of the combination of battery and generator was proposed.

(5) A new series hybrid system including an AC inverter motor, fuel economical engine and a generation regulator was examined. The total energy efficiency of it was improved by 40%.

(6) Calculation method for life cycle CO_2 emission of a series hybrid commuter-car was considered. And, effect of introducing commuter-cars upon CO_2 reduction has been estimated.

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