B - 55. 2 Evaluation of the high energy-efficiency power system for urban motor vehicles

Contact Person Kazuyuki NARUSAWA
Chief of Engine Section, Traffic Nuisance Div.,
Traffic Safety and Nuisance Research Institute, Ministry of Transport
6-38-1, Shinkawa,Mitaka-city,Tokyo,181-0004 Japan
Tel. +81-422-41-3218 Fax. +81-422-76-8604
E-mail narusawa@tsnri.go.jp

Total Budget for FY1997-1999 29,983,000Yen (FY1999 10,064,000Yen)

Abstract

A development survey of components for energy regeneration system was carried out, while the regenerative energy in urban driving of passenger cars are calculated. Next, the maximization of kinetic energy regeneration by super capacitor and storage battery was examined using a motor bench tester and a charge-discharge tester. And, the detailed evaluation method for energy transfer in hybrid electric system was considered. Based on those results, suppression effects of carbon dioxide (CO_2) discharge by introducing high-efficient automobile into urban traffic were predicted.

Key words : Energy regeneration, Storage battery, Super capacitor, CO_2 discharge

1. Introduction

About 20% of the whole CO_2 discharge in Japan is generated from transportation field, and the ratio of motor vehicles in the field is up to about 90%. Also, the increasing rate of the discharge from passenger cars is high compared with that from other transportation. Therefore, it is the most important and urgent problem to suppress the CO_2 discharge from the transportation field by improving the energy efficiency of passenger cars. Then, it is necessary to carry out the technical evaluation of high efficiency power system for passenger car that utilizes energy regeneration technology and to predict the CO_2 suppression effects by introducing such vehicles of high-energy efficiency into urban area.

2. Research objective

The objective of this study is as below.

(1) Clarify the suitable power system for urban passenger cars
(2) Maximize and evaluate the energy regeneration effects
(3) Estimate the CO2 suppression effect by introducing high energy-efficiency passenger cars

3. Results and discussions

3. 1. Calculation of effective energy and regenerative energy in urban driving

Generally, maximum energy efficiency of ordinary thermal engine vehicles is merely 20～30%. Further, in urban area, the efficiency become worse because vehicles accelerate and decelerate frequently. By a calculation based on fuel consumption and running energy, 10～15% of the chemical energy of fuel is converted to mechanical output in urban driving (1), and part of the running energy is expected to be regenerative.

Table 1 Urban driving patterns with acceleration and deceleration

Driving pattern	10-15mode	City-A	B	C	D	E
Max. speed (km/h)	70	23.7	44	49	58	69
Average speed(km/h)	30	5	11	25	22	39
Running avg. speed(km/h)	33	8	18	30	36	50
Stooping time (%)	29	42	40	14	40	22
Go-stop frequency(/km)	1.7	15.3	4.5	1.7	1.7	0.5

The urban driving patterns for the analysis is shown at table 1. The City-A is very slow speed condition in traffic jam, and the City-E relatively smooth and fast speed pattern.

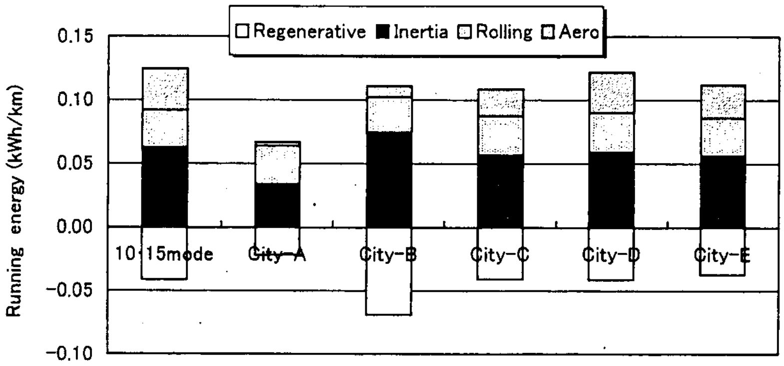

Figure 1 Required energy and regenerative energy in urban driving

Figure 1 shows the calculation result of total running energy and regenerative energy in urban driving of a small sized passenger car. The expected regenerative kinetic energy is corresponding to 20~40% of the total running energy.

3.2. Components for regeneration and suitable power system for urban passenger cars

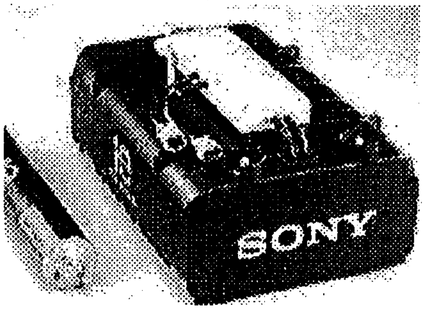

Fig. 2 Example of lithium-ion battery (2)

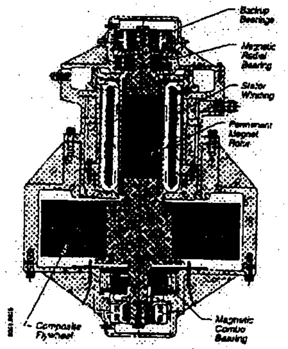

Fig. 3 Example of flywheel (4)

As advanced storage batteries, nickel-metal-hydride (Ni-MH) battery and lithium-ion battery of high energy density have been developed and applied for electric vehicles and hybrid electric vehicles practically (2). On the other hand, super capacitor and electric flywheel are also developed as different type storage devices (3)(4). They have excellent durability against repetitive charge-discharge under high current conditions. Examples of them are shown in fig. 2 and fig.3. Taking the development of these advanced components, electric motor drive system (Electric power or series hybrid electric power) that utilizes regenerative braking is thought to be suitable for urban passenger cars.

3.3. Experiment for maximization and evaluation on energy regeneration

(1) Testing equipment and condition

A simulated electric city commuter-car was set on a bench test equipment. A set of super capacitor was used with battery as energy storage device. Fig. 4 shows the outline of testing system. The traction motor was set on the end of the bed, and equivalent driving load was generated by inertia disks and electromagnetic brake. The maximum storage energy of the capacitor is corresponding to 0.7% of the battery energy. As circuit connection, "Switching", "Parallel" and "Battery only" were operated. In case of "Switching", the capacitor was selected to absorb the regenerative power prior to battery in braking. Capacitor energy was released at the next acceleration in case of "Switching-1" , and it was held until the capacitor voltage rises to the upper limit in case of "Switching -2" (5).

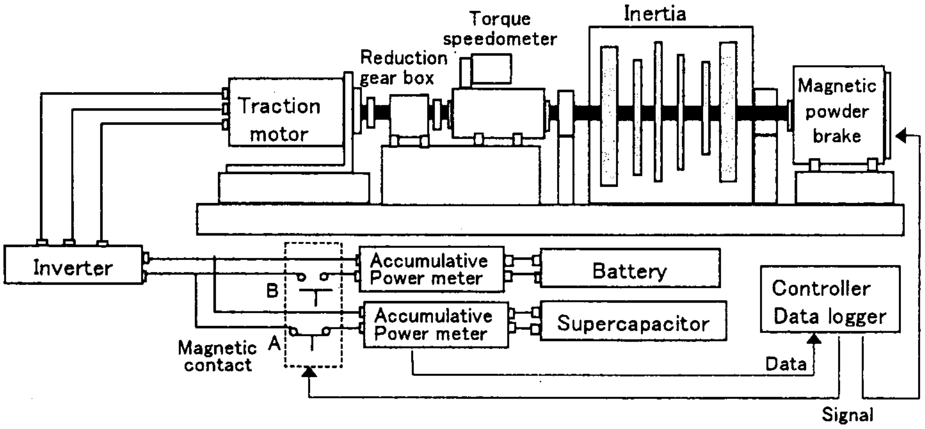

Fig. 4 Bench testing system

(2) Experimental result

In fig.5, braking power in the deceleration and the absorption capacity of the battery are shown. In case of the slow deceleration, it is possible to absorb the braking power only by the battery. But in case of the steep deceleration, braking power may exceed the absorption capacity of the battery in the initial stage. However, it is thought to be able to absorb such high braking power by adding capacitor .

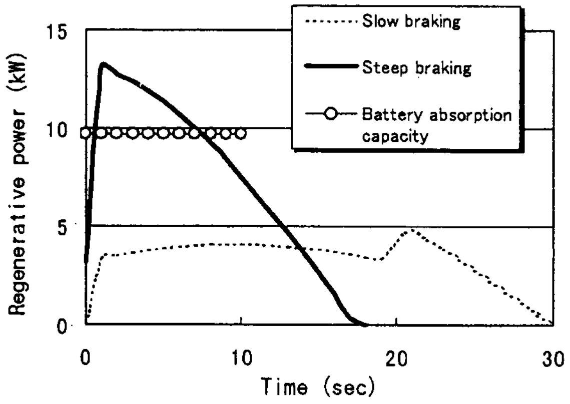

Fig. 5 Braking power in the deceleration and absorption capacity of the battery.

Fig.6 ~ Fig.9 show the examples of measurement results of the energy absorption by capacitor and battery in urban driving. In the City-A driving, the total absorbed electricity in case of the "Switching-1" was 30% over than that in case of the "Battery only". In other driving patterns excluding the City-A, the total absorbed electricity in case of the "Switching-1" was 10% - 15% over than that in case of the "Battery only" connection. The measured values of the absorbed electricity were up to 80% of the calculated values. In the City-A, regenerative voltage was low because of low vehicle speed. On the other hand, in the City-E, regenerative power rose steeply and exceeded the absorption capacity of the battery in steep braking from high speed. It was impossible to absorb such regenerative power only by the battery. But by applying the capacitor with the "Switching-1", as the voltage difference between the inverter and the absorption device can be much, so the absorption of regenerative electricity was promoted extremely.

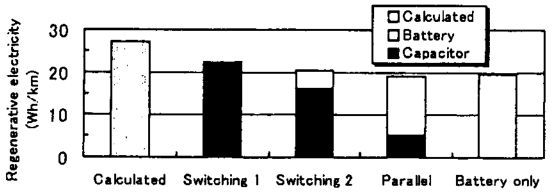

Fig. 6 Energy absorption in 10-15 mode

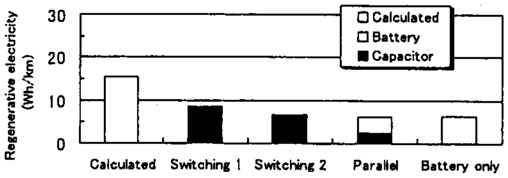

Fig. 7 Energy absorption in City-A

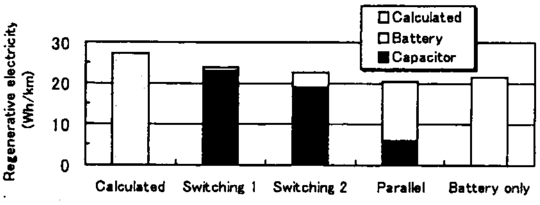

Fig. 8 Energy absorption in City-C

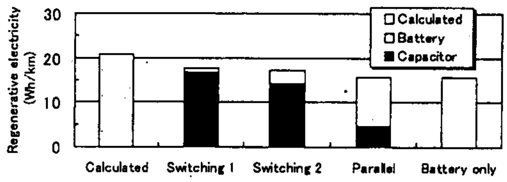

Fig. 9 Energy absorption in City-E

Fig. 10 shows the input electricity and the output electricity measured in the braking-accelerating tests under the "Switching-1" or the "Parallel". In case of the "Switching-1", the output electricity was correspond to 50 % of the input electricity by slow pattern and steep operation, so losses with charge-discharge was thought to be much. On the other hand, in case of the Parallel connection, the output electricity was nearly equal to the input electricity, so loss was thought to be very few. So, it is thought that the operation of "Switching-1" has an advantage of electricity absorption, however it has disadvantage of energy re-use. In order to reduce such losses, it is necessary to lower the internal resistance of the capacitor and to consider proper devices that can control the capacitor output current.

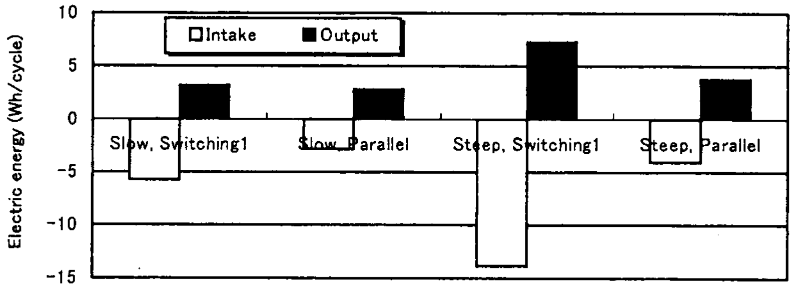

Fig. 10 Capacitor in-out energy per one cycle of deceleration and acceleration (70km/h - 50km/h)

3.4. Clarifying of energy flow in hybrid electric power system

(1) Testing equipment and condition.

The motor system of the commuter EV was replaced with a charge-discharge tester, and the simulated series hybrid electric power system was constituted by the connection of battery, capacitor and generator (DC power source) shown as fig. 11. The charge-discharge tester can automatically reproduce the electric current in-out conditions of the series hybrid system on the actual urban vehicle driving.

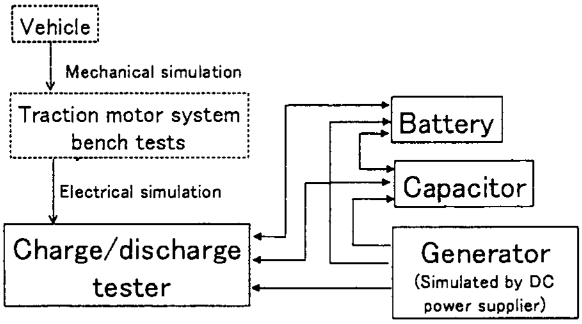

Fig. 11 Outline of electrical simulation by charge-discharge tester

(2) Experimental results

The possible patterns of the electric flow under the fig.11 construction are counted over 50 cases by a simple calculation. In table 2, some flow patterns are shown. For example, the Flow-A occurs in slow acceleration, otherwise the Flow-B occurs in steep regenerative braking.

Table 2 Example of electricity transfer pattern in series hybrid system
(G : Generator B : Battery M : Motor system C : Capacitor)

Name	Electric flow pattern
Flow A	G→B G→M G→C
Flow B	G→B M→B M→C
Flow C	G→M B→M C→M
Flow D	G→B G→M G→C
Flow E	G→M G→C B→M B→C
Flow F	G→B

The frequency distribution and the time-share of each flow pattern in case of the Japanese 10-15 mode driving are shown in fig. 12 and fig. 13.

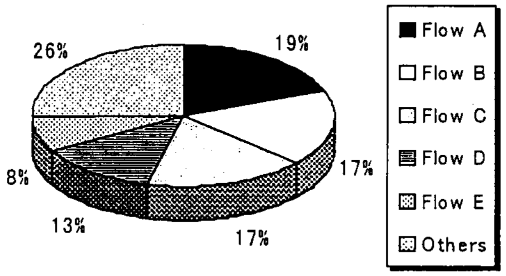

Fig. 12 Frequency distribution of electric flow pattern (10-15 mode)

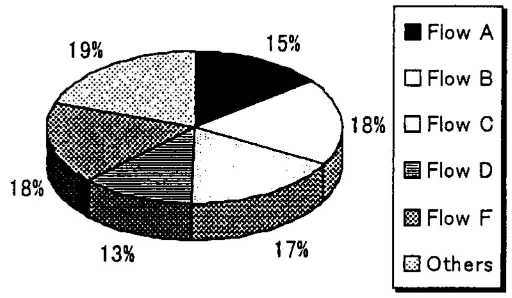

Fig. 13 Time-share of electric flow pattern (10-15 mode)

The frequency distribution and the time-share of the Flow-A~Flow-D occupies 10~20% for the total respectively. The Flow-F occurs only in stoppage, and the frequency is very little, but the time-share is near 20% for the total.

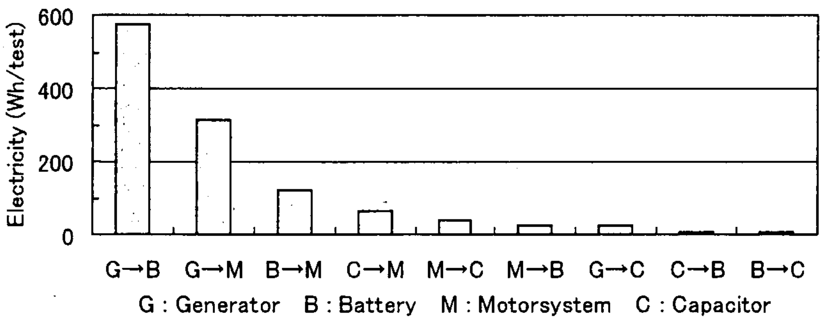

Fig. 14 Transfer electric energy between each elements in the 10-15 mode operation (G : Generator B : Battery M : Motor system C : Capacitor)

Fig. 14 Shows a result of the quantity of electric flow among components in the10-15 mode driving. According to this result, the output electricity from the generator to the battery is the largest, and the output electricity from the generator to the motor system follows this. A small amount of electricity transfers between battery and capacitor.

Energy loss is generated during the in-out process of electric flow through battery, capacitor and motor system. Therefore, in order to evaluate the total energy efficiency of the series hybrid electric power system preciously, it is thought to be necessary to analyze electricity flow pattern by methods mentioned above.

3.5. Prediction of CO_2 reduction effect by introducing high-efficiency passenger cars.

(1) CO_2 reduction per one vehicle by conversion to EV or HEV.

In order to estimate the reduction effect of the life cycle CO2 discharge (hereafter referred to as "$LCCO_2$") by converting ordinary thermal engine vehicles to EV or HEV, seven types of passenger cars were assumed as shown in table 3. In case of the base engine-car, it was also assumed that 13% of the $LCCO_2$ was originated in manufacturing stage and the remainder was originated in use stage.

Table 3　The weight of assumed passenger cars (unit kgf)

Type	Vehicle weight	Battry weight	Capacitor weight	Battery renewal
Engine vehicle (Base)	1000	0	0	None
EV- 1	1300	300	0	None
EV-2	1300	300	0	Once
EV-3	1350	300	50	None
HEV-1	1250	50	0	None
HEV-2	1250	50	0	Once
HEV-3	1300	0	100	None

Fig. 15 shows a $LCCO_2$ estimation result in which the deference between the engine-car and the EV-1 was taken into consideration step by step. As the EV-1 is 300kgf heavier than the base engine-car, so the CO_2 discharge both in manufacturing stage and in use stage may increase. Therefore, by simple calculation, the $LCCO_2$ of the EV-1 become 22% more than the base.

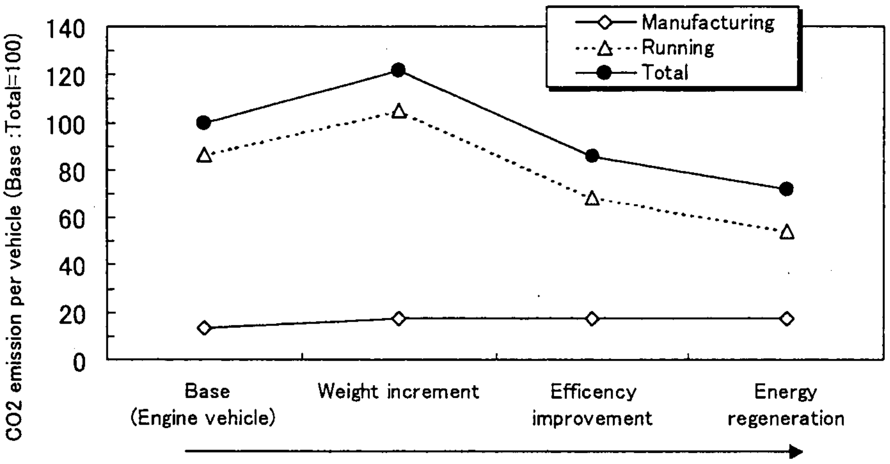

Fig. 15　CO_2 discharge by EV compared with engine car (Engine car =100)

At the next step, taking into consideration that the energy efficiency of electric power system is much higher than that of the thermal engine, the CO_2 discharge in use stage may decrease by 35%. Further, 20% of running energy is thought to be regenerated in braking. Totally, the $LCCO_2$ of the EV-1 is estimated to be 30% less than that of the base engine-car.

Fig.16 shows the $LCCO_2$ estimation results of various EV and HEV in comparison with the base engine-car. The $LCCO_2$ of the EV-1 is 1.72Mt less than that of the base engine-car, however that is 1.47Mt less than that of the base if battery renewal is required. As the EV-3 has excellent energy absorption ability and does not need battery renewal owing to capacitor, so it achieves equivalent CO_2 reduction effect to the EV-1 though the vehicle weight is heavier than the EV-1. Also, the $LCCO_2$ of the HEV-3 is 0.4Mt less than that of the EV-2. Taking its long running range into consideration, the HEV-3 is thought to be most advantageous to suppress CO_2 discharge.

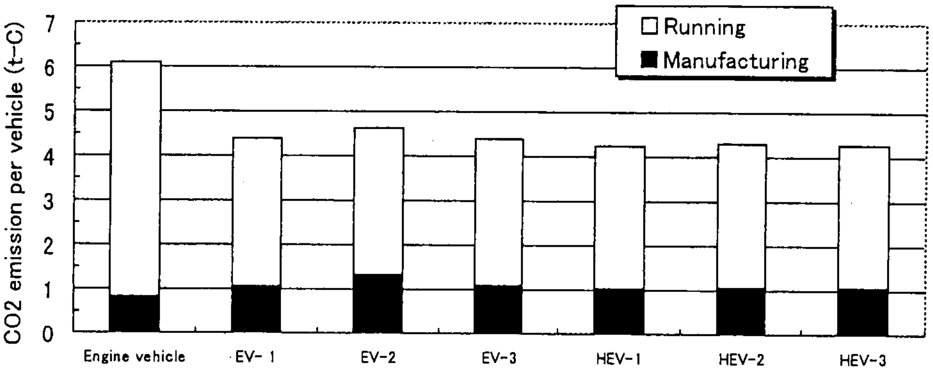

Fig. 16 LCCO$_2$ of EV and HEV

(2) Total CO$_2$ reduction effects by introducing EV or HEV into urban area

In Japan, the number of the passenger car in urban area is about 13,500,000 units, and it corresponds to 1/3 of the whole passenger car as shown in Fig. 17.

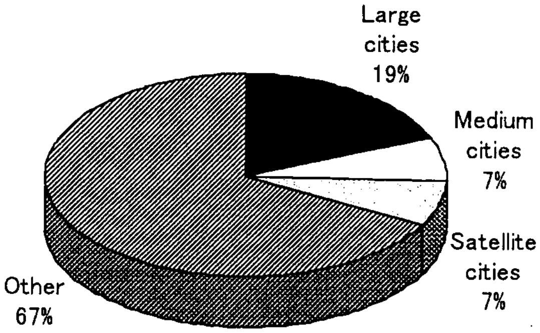

Fig. 17 Share of urban passenger cars

Fig. 18 shows a calculation result of the whole LCCO$_2$ from urban passenger cars on the assumption of partial replacement from ordinary engine-car to EV or HEV. For example, the 30% replacement to the EV-2 may reduce the whole LCCO$_2$ from urban passenger by 8%.

Further, as the best case, the 50% replacement to the HEV-3 may reduce the whole LCCO$_2$ from urban passenger cars by 15%..

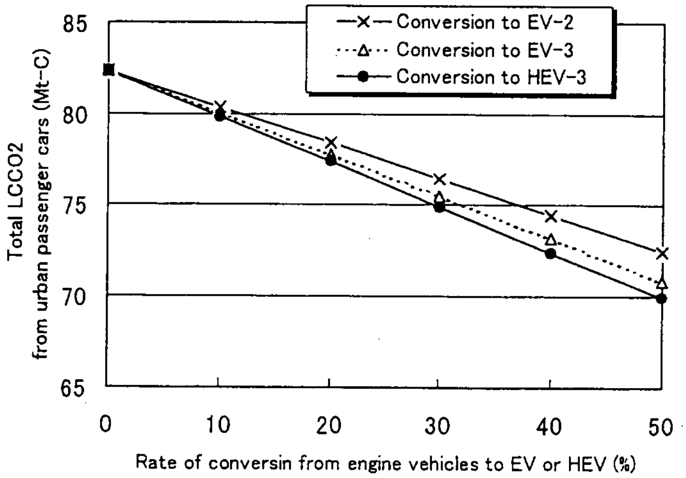

Fig. 18 CO$_2$ reduction by replacing urban passenger cars to EV or HEV

4. Summary

(1) Percentage of usable energy of fuel and regenerative energy in urban driving of passenger car were calculated. It is expected that 20～40% of the running energy for the total can be regenerative.

(2) A development survey of advanced components for energy regeneration was carried out. On the base of the results, the components of electric power system and series hybrid electric power system was selected for urban passenger cars.

(3) Motor bench tests of urban driving were carried out. By applying the super capacitor with switching operation, the absorbed regenerative electricity is increased by 10% - 30% compared with that in case of the battery only. It is proper to use the super capacitor with the battery by the switching operation, and to discharge the capacitor frequently.

(4) A simulated series hybrid power system was built up with a charge-discharge tester and some components. Patterns, frequency and quantity of electricity flow were examined in order to evaluate energy efficiency of the hybrid system preciously.

(5) The life cycle CO_2 discharge ($LCCO_2$) of the high energy-efficiency cars (EV or HEV) was estimated in comparison with that of the ordinary engine-cars. Further, the whole CO_2 reduction effect by replacing ordinary cars to EV or HEV in urban was predicted.

References

(1) N.Iwai, "Development and overview of future high-efficient clean energy vehicles", Japan Automobile Research Institute Vol.19th No.6th, P.169 (1997)

(2) Japan Electric Vehicle Assoc., Material " EV World ", 1997.

(3) T.Saito et al, "Development of High-power Electric Double-Layer Capacitors", the NEC RESEARCH & DEVELOPMENT Vol.36, No.1, P. 193-198 (1995)

(4) M.A.Pichot et al. "The Flywheel Battery Containment Problem", SAE Paper 970242 (1997)

(5) K.Watanabe et al, "Development of a Braking Energy Recovery System", JSME The 6th. Transportation and Logistics Conference proceedings, P.277 (1997).

(6) Y.Moriguchi et al, "Analyzing the life cycle impacts of cars : the case of CO2" UNEP Industry and Environment January - June 1993