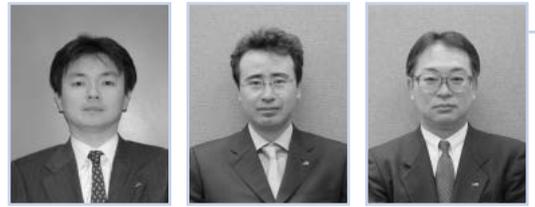


Development of an NE train



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Through innovation of the power system using fuel cells or hybrid systems, JR East has been developing an "NE train (New Energy Train)" which would reduce the effects on the environment by train cars. As the first step, we completed a test train equipped with a hybrid system. This was the first train car to use a hybrid system. Starting from May 2003, we started test runs on the Nikko and Karasuyama lines in order to check its system performance and energy conservation effects. From January 2004, we then started test runs in cold regions to check its performance. As a result, sound hybrid system control was confirmed.

● **Keyword** : hybrid system, lithium-ion secondary battery, diesel engine, fuel cell

1 Introduction

Energy used for train operation accounts for approximately 70% of the total energy consumed in business operations by railroad companies, and one of our objectives for prevention of global warming is to discover ways to improve energy consumption efficiency.

Energy conservation has been practiced through "weight saving," "improvement of efficiency of the power plant and transmission gear," and "recycling of brake energy (regenerative braking)." However, regenerative braking cannot be configured in diesel cars that run within unelectrified line districts; therefore, energy efficiency for diesel cars is believed to be approximately 30% lower than that of electric cars.

Thus, we set improvement of diesel car energy efficiency as one of our goals and developed an NE train that would reduce environmental burdens through innovation of the power system.

As the first step, we completed a test train equipped with a hybrid system. This was the first train car to use a hybrid system. Starting from May 2003, we started test runs in districts on the Nikko, Karasuyama and Tohoku lines in order to check its basic performance, hybrid system performance, and energy conservation effects.



Fig.1: NE train

2 Development concept

Compared to electric cars, diesel cars have the following issues:

- (1) They have lower energy efficiency than electric cars.
- (2) Their engines generate exhaust gasses and noises.
- (3) They use a large number of machine parts, resulting in a large volume of maintenance work.
- (4) Their accelerative force is low in medium and high speed areas, resulting in low running performance.

We thus defined the development concept of the NE train as "harmony with the environment" and "shift to train technology," and

specifically, we set our goals as "energy conservation," "reduction of toxic substances in exhaust gas and reduction of noise," "reduction of maintenance work," and "the same level of running performance as electric trains." As for actual development, we planned to use "fuel cells" which could dramatically reduce environmental burdens in the future, and also to implement for the time being a hybrid system consisting of a "diesel engine" and "capacitor" which could be put into practice at an early stage.

3 Overview of development

3.1 Selection of a hybrid system

The hybrid systems used in road vehicles are categorized as: the series hybrid system; the parallel hybrid system; and the series-parallel hybrid system, which has characteristics of both of these systems.

For development of the "NE train," we selected the series hybrid system for the following reasons:

- (1) In the series hybrid system, shifting of the power system to a fuel cell system in the future can be done simply by replacing the engine with a fuel cell.
- (2) Since railroad cars go forward and backward along the same lines, a mechanism such as a reversing gear would need to be installed if the parallel hybrid system were used.
- (3) Electric train technologies can be effectively used in the series hybrid system. Therefore, devices can be shared between electric cars and NE cars, resulting in cost reduction and reduction of maintenance work. Also, the level of running performance will reach

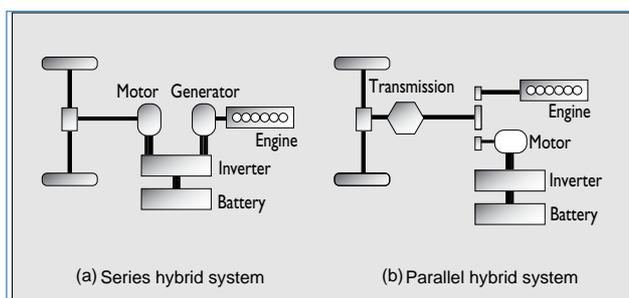


Fig.2: Comparison of hybrid systems

the level of electric cars.

- (4) It is possible to maintain constant engine revolutions in the series hybrid system. Therefore, the engine can always be used at its optimal fuel efficiency and with a minimum amount of exhaust fumes.

3.2 Main motor and engine power

Power of the main motor for the NE train depends on the required power performance:

- (1) Electric car type tractive characteristics
- (2) Grade ability at the same level as that of a new model railcar (25%, equilibrium speed: 60 km/h)

In order to ensure the above performance, we decided to use two main motor units (95 kW) that had a good track record with Series E231 electric commuter cars. Their heat capacity was tested through operation simulations based on the actual operation line districts and was found to guarantee sufficient capacity.

The power of the engine generator was selected on the condition that individual operation of an engine would still ensure the following car performance even if the stored battery capacity drops to a low level while running in an area with continuous slopes:

- (1) The abovementioned grade ability is ensured.
- (2) Power output from the engine only can still allow acceleration up to the maximum speed.

As a result, we opted to use an engine generator of 330 kW (2100 rpm) power output. This engine is a newly-developed eco-friendly engine that can reduce more than 30% of Nox & PM.

3.3 Selection of a capacitor

3.3.1 Types of capacitors

Energy efficiency of the hybrid system depends on the capacitor for

storing regenerative energy. Practical examples of such capacitors are electric double-layer capacitors, flywheels, and secondary batteries. Since the selected capacitor must be installable in a train car, power density and energy density per unit of weight become important indices for the selection. Table 1 shows performance comparison among typical storage batteries.

Table 1: Performance comparison among capacitors

	Energy density (Wh/kg)	Power density (W/kg)	Life (cycle)	Cost
Electric double-layer capacitor	6	500		
Lead storage battery	40	300		
Nickel metal hydride battery	40 ~ 70	200 ~ 700		
Lithium-ion battery	30 ~ 130	30 ~ 1400		
Flywheel	~ 50	1000 ~		

Since railcars demand a high level of energy output, capacity, and safety as well as stability, use of a nickel metal hydride battery or lithium-ion battery seems to be the most appropriate. In fact these capacitors are used in many hybrid road vehicles. Although the most commonly used battery for road vehicles is the nickel metal hydride battery because of its cost, high performance such as the power density of a lithium-ion battery is still highly attractive. For the NE train, we opted to use the lithium-ion battery with expectation for its future potential. When considering current development, the use of this battery can also be expected to reduce the cost and extend its life.

3.3.2 Capacity of a capacitor

A capacitor with larger capacity can realize high energy efficiency since it will allow averaging of engine power generation, expansion of idling stops of the engine, and reduction of charge/discharge loss of a capacitor. Currently, however, the cost of a lithium-ion battery per output of 1 kW is several times higher than that of an engine, and for an NE test train, therefore, a lithium-ion battery of a minimum capacity that was sufficient for securing energy efficiency was included in the system design.

The following items have to be discussed when determining a specific capacity:

(1) Capacity for storing regenerative braking energy

※ Average braking energy used for making a single stop

⇒ Approximately 1 kWh

(2) Electric energy necessary to run a railcar along a flat area

※ Electric energy necessary to run a railcar for 5 km between stations

⇒ Approximately 3 kWh

Also, for the NE train, we decided to use a battery within the SOC range of 20% to 60%, taking the life and output of the capacitor into consideration.

As a result of a comprehensive review of all the items discussed above, the capacity of the lithium-ion battery was determined to be 10 kWh.

3.4 Power control system

3.4.1 Overview of an energy management and control system

For development of a hybrid system, the question of "how mechanical energy and electrical energy should be integrated" is an important point regarding the power control system. There are the following requirements:

(1) The power control system should effectively store regenerative energy in terms of power conservation.

(2) The generator engine should be used at its optimal efficiency.

Also, in terms of the noise and exhaust issues:

(3) When a railcar is running slowly inside a station or is making a stop, capacitor output should be mainly used, and the engine should not be operated unless necessary.

In consideration of these requirements, we developed a unique

power control system for the NE train.

Figure 3 shows the flow of control information between the units. In this energy management and control system, information from individual units such as a secondary battery, inverter and converter, main motor, and diesel engine is all collected and reflected in acceleration/deceleration of the car or in control of engine power generation.

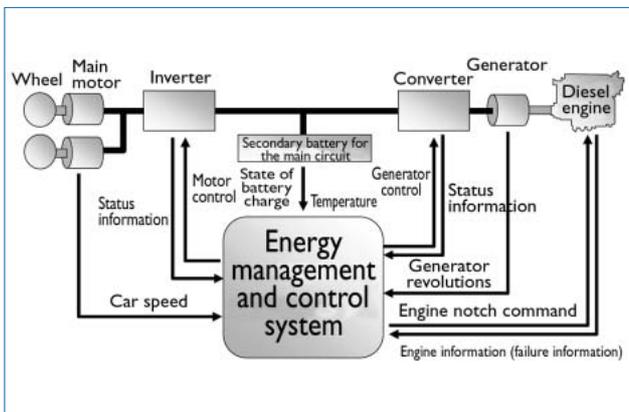


Fig.3: Overview of the energy management and control system

3.4.2 Basic principle of the energy management and control system

The basic principle of this system is to control power generation of the engine in such a manner that "the sum of energy generated by the car motion (which changes with car speed) and stored energy (stored in the battery) is kept constant regardless of speed."

When the car speed is increased, energy generated by the car motion, or the potential regenerative energy of the car, is also increased. Therefore, the battery should be charged less while the car is in motion than the time when the car is not in motion, or the regenerative energy cannot be collected when the brake is used. In other words, the appropriate state of battery charge changes with car speed, and the system should be controlled so that the battery can be charged to that appropriate level until the engine power generator starts to operate.

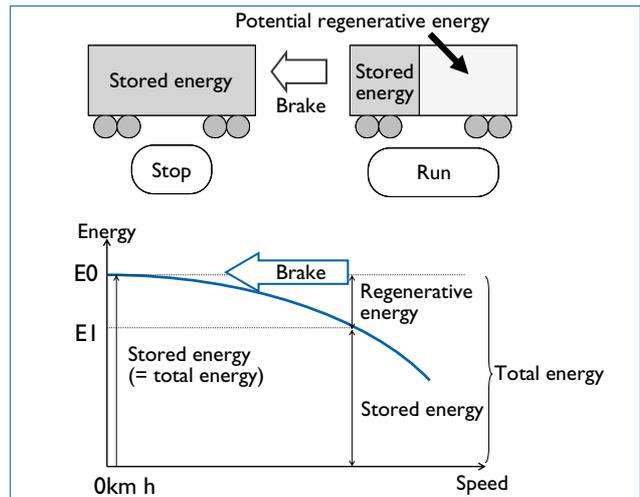


Fig.4: Basic principle

3.4.3 Energy management and control diagram

The "energy management and control diagram" (Figure 5) is a representation of the concept of engine output control based on car speed and the state of battery charge, in accordance with the basic principle mentioned above.

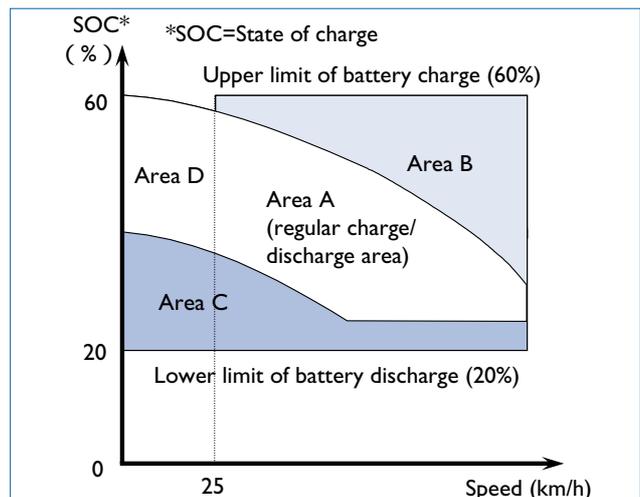


Fig.5: Energy management and control diagram

SOC is an index to indicate the status of battery charge. Taking the life of a secondary battery into consideration, it is generally desirable that the battery be charged and discharged within as small a capacity range as possible. Referring to the past record of hybrid road vehicles, we decided to control charge/discharge of the battery within

the range from 20% to 60%.

In the diagram, the graph is divided into four areas depending on the relationship between car speed and the charge status.

The curved lines above and below area A are set based on the basic principle of energy management and control described above. The line above the area refers to the limit line for reserved capacity of battery charge, and the line below the area refers to the limit line for reserved capacity of battery discharge.

(1) Area A (regular charge/discharge area)

The engine generates power at its optimal fuel consumption rate. The system should be controlled so that the secondary battery will charge/discharge within this range.

(2) Area B

If the battery is further charged, it will be over-charged for its car speed. Therefore, the system attempts to stop power generation by the engine and return the status of charge to area A. In terms of the engine responsiveness, the engine is essentially in the idling state.

(3) Area C

The capacity of the secondary battery is extremely low for car speed in terms of line district, operation, and environmental conditions. In this case, the engine generates power at its maximum output level in order to return the charge status to area A.

(4) Area D

Idling stop inside a station is considered to be an engine stoppage.

3.4.4 Major car control mode

Major car statuses are as follows:

- 1) Departure from a station: The car is set into motion on battery power. The power generating engine starts operating when the car accelerates.
- 2) During cruise: The power generating engine operates at its highest efficiency, and the secondary battery discharges/charges depending on running loads.

3) While running up a slope: The power generating engine operates at its maximum output level.

4) While running down a slope: The battery is charged by the regenerative brake. Car speed is controlled by the engine exhaust brake.

5) When braking: The power generating engine stops. The battery is charged by the regenerative brake.

6) When making a stop at a station: The power generating engine stops. Service energy is supplied from the battery.

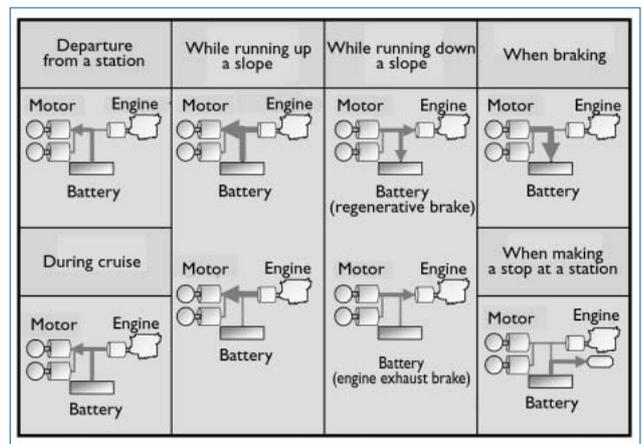


Fig.6: Major car control modes

3.5 Overview of the test car

The test car used in this test consisted of only one car, which was the smallest test unit that was able to individually operate. Also, in order to most effectively use our train technologies, we made various devices standardized and compatible with the latest electric trains. The train body used was a stainless steel body which was the same as Series E127 railcars that ran on local lines. As for the truck, motor, and controller, the same ones as Series E231 railcars were used although some adjustments were made to the voltage due to the capacitor properties. Two trucks were used and one of them was motor-driven. The capacitor was installed on the roof of the test car just as the brake resistor of Series E127 railcars. Figure 7 shows the overview of the test car, and Table 2 shows the specifications of the same.

Table 2: NE train specifications

Technical maximum speed	100km/h	
Model	Ki Ya E991	
Overall length	20,000mm	
Car length	19,500mm	
Car width	2,800mm	
Roof height	3,655mm (maximum height: 4051.5 mm)	
Distance between truck-centers	13,800mm	
Truck model	DT959 (front)	TR918 (rear)
Major devices	Main motor	MT936 x 2 (induction motor 95 kW x 2)
	Main controller	CI905
	Secondary battery for the main circuit	Lithium-ion battery (10 kWh)
	Engine for power generation	Diesel engine (331 kW / 2100 rpm)
	Main generator	DM927 (induction motor 180 kW)
	Auxiliary power unit	SC934 (45kVA)
Motor-driven air compressor	385NL/min	
Brake type	Electric command air brake for recovering and generating power, holding brake, and straight air reserve brake	

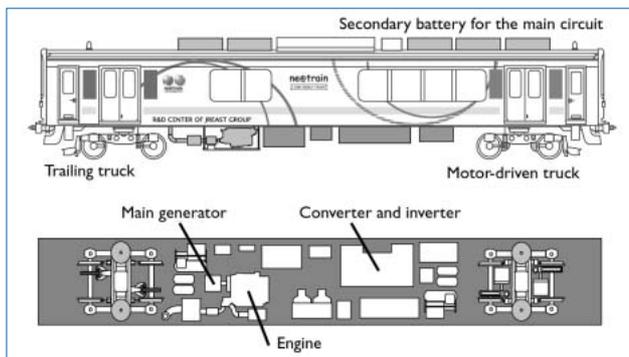


Fig.7: Overview of the NE train

4 Evaluation test

4.1 Test plan

The following items were evaluated through the running test using the test model:

- (1) Basic car performance (acceleration and braking deceleration)
- (2) Abnormal event simulation (battery cut-off, running with cut-off engine)
- (3) Energy management and control (control method and energy conservation effects for each line district)
- (4) Environmental responsiveness (evaluation of temperature

characteristics of the secondary battery)

The running test was conducted from May to September 2003 on the Nikko, Karasuyama, and Utsunomiya lines in order to conduct performance evaluation and check basic car performance and control of the hybrid system. Since November 2003, we have been conducting tests on Nikko line to check the energy conservation effects in each line district. At the same time, tests have been conducted also on the Rikuuto and Kamaishi lines in order to check car performance in cold regions.

4.2 Test results

In the running tests conducted on the Nikko, Karasuyama, and Tohoku lines, the following performance items were reviewed:

- (1) Basic car performance

As a result of the tests, it was confirmed that the car had the designed performance (acceleration/deceleration ability at the same level as electric cars).

Acceleration performance: $\alpha = 2.3$ km/h/s (at 35 km/h)

Deceleration performance: $\beta =$ higher than 3.6 km/h/s

- (2) Abnormal event simulation

- ① Running with cut-off engine

The car was able to accelerate up to 70 km/h with the use of only the battery (travel distance: 2 to 3 km)

- ② Running with cut-off battery

It was confirmed that the car could run with only the engine when the battery is cut off due to failures.

- (3) Power control system

- ① Idling stop of the engine

It was confirmed that the engine stopped (for more than 5 minutes, although it depended on the air-conditioning load) when the car stopped at a station, and that the engine remained off when the car

started again (until it reached approximately 25 km/h).

②Rate of energy regeneration

It was about the same level as what was simulated (approximately 20%).

(4) Environmental responsiveness

①Performance test in hot regions

Car performance was examined under outside air temperature of 35 °C, and no abnormalities were found.

②Performance test in cold regions

Car performance tests are currently being conducted under sub-zero temperatures.

For each item, the tested hybrid system demonstrated virtually all the planned functions.

Figure 8 shows the actual running test data conducted on Utsunomiya line (between Nishinasuno and Nozaki)

From the curved line showing "engine revolutions" at the time of departure from Nishinasuno and Nozaki stations, it is possible to see that the engine had been stopped when the car was at the stations

and started to operate when the car speed reached 25 km/h. Also the figure indicates that the engine increased its output from "2N (1700 rpm)" to "3N (2100 rpm)" when the car speed reached approximately 80 km/h. After that, the engine gradually switched its power generation and output between "idling," "2N," and "3N" depending on the status of charge of the secondary battery.

From the curved line showing the "status of charge of the secondary battery," it is possible to see that the regenerative brake allowed the battery to charge electrical power of approximately 1.5 kWh when the brake was used to stop the car at Nozaki station. The graph also indicates that, although only a little, the regenerative brake operated until the car speed decelerated to 5 km/h.

Figure 9 shows the measurement data obtained from the running tests conducted on Nikko line (between Nikko and Imaichi). There is a continuous slope of approximately 25‰ between these stations.

The NE train has the "holding braking" function that keeps the car speed under a certain speed level on a downward slope.

This brake can be controlled in 2 stages. In Stage 1, the battery absorbs regenerative energy. In Stage 2, if the battery charge level reaches a high level, the exhaust brake of the engine consumes the

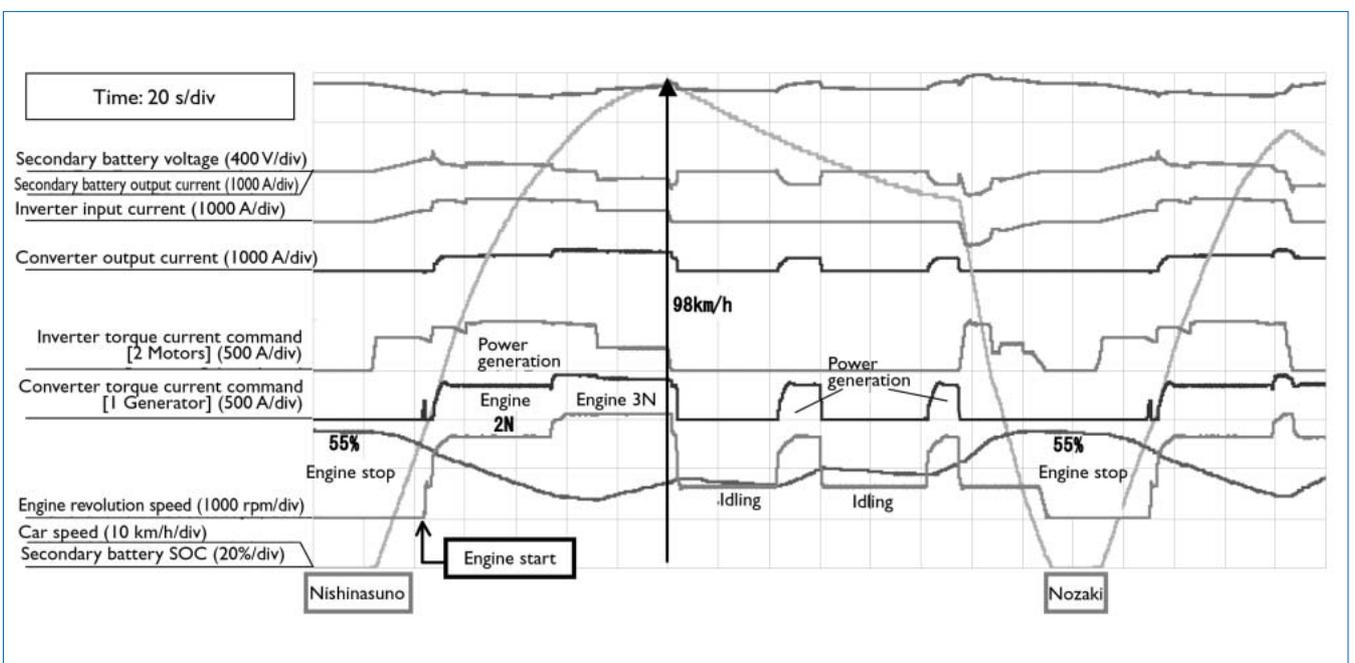


Fig.8: Running test chart (Nishinasuno to Nozaki)

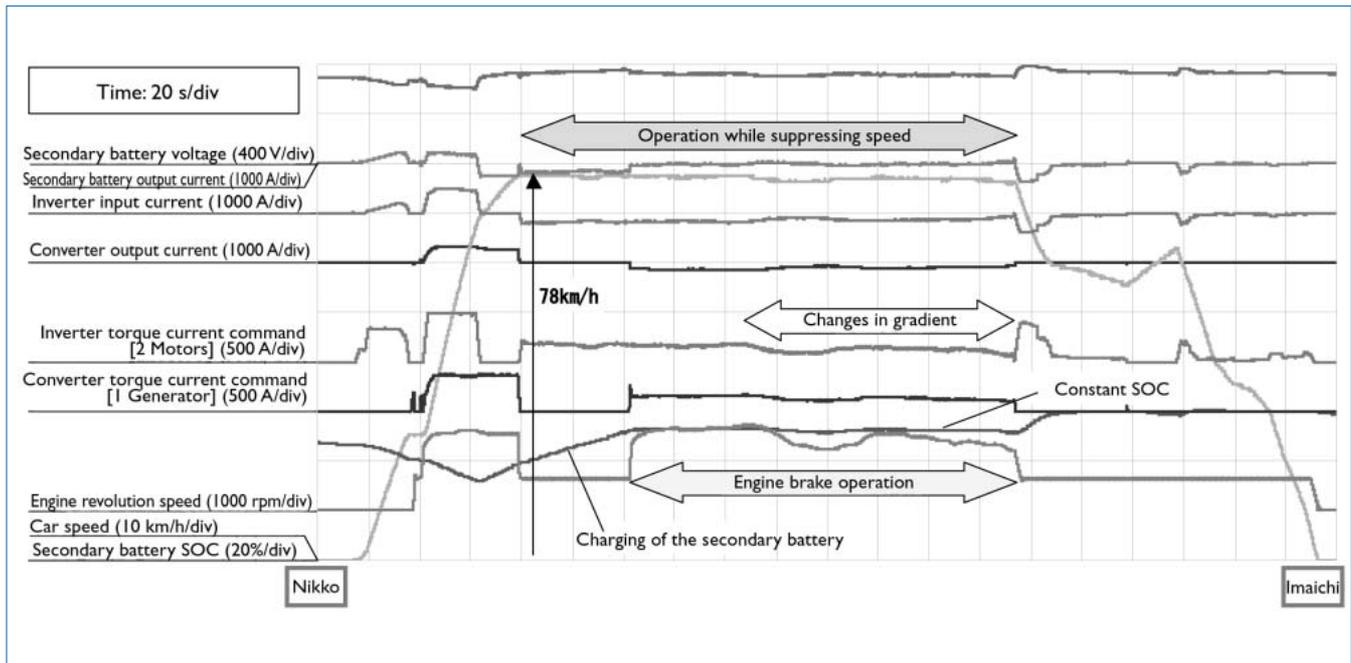


Fig.9: Running test chart (Nikko to Imaichi)

brake energy. As seen in this chart, the engine was in its idling state for a little while after the holding brake started to operate, and meanwhile, the "secondary battery SOC" rose. Then, when the SOC reached a certain level, the engine revolutions frequently changed with changes in gradient. This means that the engine exhaust brake was functioning.

(Note) N: notch

4.3 Energy conservation effects

In general, the shorter the distance between stations, the better the hybrid system can use regenerative energy; therefore, it can have higher energy efficiency than a diesel system. However, if there are many long slopes, an increased volume of energy will be consumed while going up a slope and also a large volume of brake energy can be obtained while going down a slope. Therefore, it will not be possible to effectively use all the available energy, and there will be the problem that ideal energy efficiency cannot be ensured. We then conducted a simulation of "regenerative energy efficiency = regenerative energy/running energy" on a few lines including the Nikko and Karasuyama lines based on their line district conditions.

According to the simulation, regenerative energy efficiency of approximately 20% could be expected although it differs with individual district conditions.

The figure below shows comparison between the result of the simulations and the result of running tests conducted thus far.

Values for the regeneration ratio obtained through the simulation and the running tests were approximately the same. Also, running tests have been conducted since January on Rikuuto line and Tohoku line (from Morioka to Kitakami), and the obtained values were 25% and 23% respectively. Therefore, the regeneration ratio was approximately 20% as a result of the running tests.

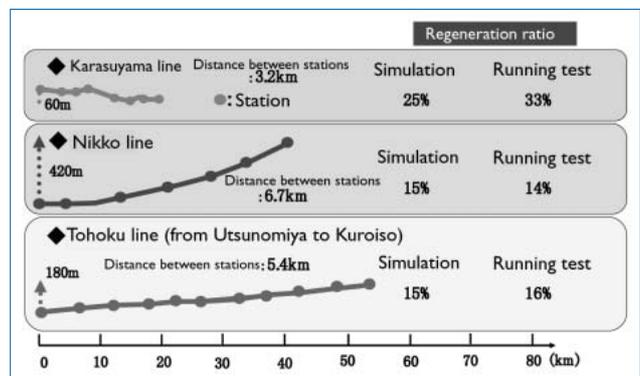


Fig.10: Comparison of energy regeneration ratio in each line district

5 Conclusion

Examination of basic car performance and system performance has mostly been completed, and now important tests such as environmental responsiveness tests and endurance tests of secondary batteries are planned. Through these examinations, we hope to establish the hybrid system for railcars as early as possible. The power control system described above underwent a large number of detailed adjustments using important know-how learned during the course of running tests and thus we arrived at the current system. Compared to road vehicles that run on streets under various conditions, railcars run on predetermined line districts; therefore, implementation of a control method that incorporates individual line district conditions may be a future possibility. Also, along with these performance issues, cost reduction for the purpose of practical use of the system is another important issue. We will make further efforts and work on these issues to achieve the practical use of an eco-friendly NE train.