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Research and Development at RTRI toward the Achievement of Net-Zero by 2050

Message from New Managing Editor Dr. Toru MIYAUCHI

Dr. Toru Miyauchi
Managing Editor
Associate Director (International Affairs),
Research & Development Promotion Division

As of 1 April 2022, Railway Technical Research Institute (RTRI) was reorganized and I became Associate Director (International Affairs), Research & Development Promotion Division and new Managing Editor of Ascent.

Under the main theme "Research and Development at RTRI toward the Achievement of Net-Zero by 2050", this issue introduces energy-saving technologies developed by RTRI such as a fuel cell hybrid train, superconducting technologies and a train operation power simulator.

I hope this issue has succeeded in presenting perfect-match solutions to the needs of the railway world. Your continued interest in Ascent is highly appreciated.

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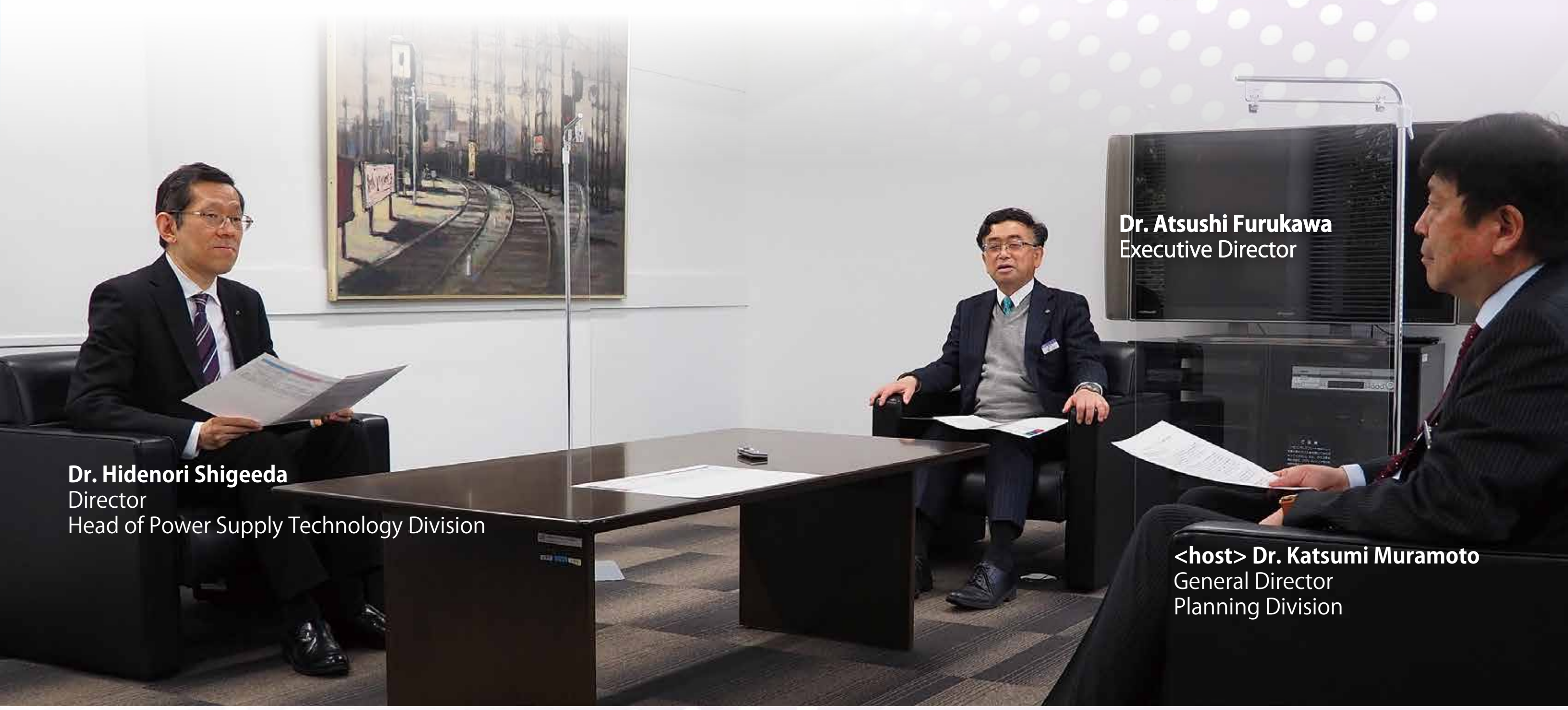


Research and Development at RTRI toward the Achievement of Net-Zero by 2050

Muramoto On November 10, 2021, RTRI hosted a lecture session with the theme “Railway Technologies Required for decarbonization.” This was the first time RTRI has announced decarbonization as a major research goal and publicly shared our prospect of research and development on this net-zero carbon emissions. It has been about 6 months since both of you made presentations at the session. Today, I would like you to talk about RTRI’s research and development of the achievement of net-zero by 2050.

First, I would like Dr. Furukawa to review RTRI’s research efforts over the last year. Dr. Furukawa delivered a keynote speech as executive director responsible for the Research and Development Promotion Division at RTRI.

Furukawa In recent years, management of railway operators have been increasingly interested in decarbonization. In particular, since the then prime minister Suga set Japan’s goal of achieving net-zero by 2050, they have asked us frequently, “What is RTRI doing to contribute to this goal ?” This is one of the reasons why we chose decarbonization in the railway sector as the theme of the session.

In the past, we haven’t conducted research projects featuring “decarbonization” as their major goal, but we have done a lot of research to reduce energy consumption in train operation. In the session, we focused on two aspects of decarbonization:

reducing CO_2 emissions and reducing energy consumption, in other words, "energy saving." We also reviewed our research and development achievements, classifying them into the two aspects, and presented the prospect of our research of the achievement of net-zero by 2050.

Furthermore, in 2022, we started to include in RTRI's business plan "decarbonization of railways of the achievement of net-zero by 2050" as one of our research policies. In addition to starting new decarbonization projects, we will further intensify the research in the on-going projects to contribute to this goal.

Muramoto I think this is what we need to do and all of the research divisions and sections at RTRI need to address.

Now we would like to hear about future prospects of decarbonization of railways from Dr. Shigeeda. Dr. Shigeeda is Director of Power Supply Technology Division that covers core technologies regarding decarbonization.

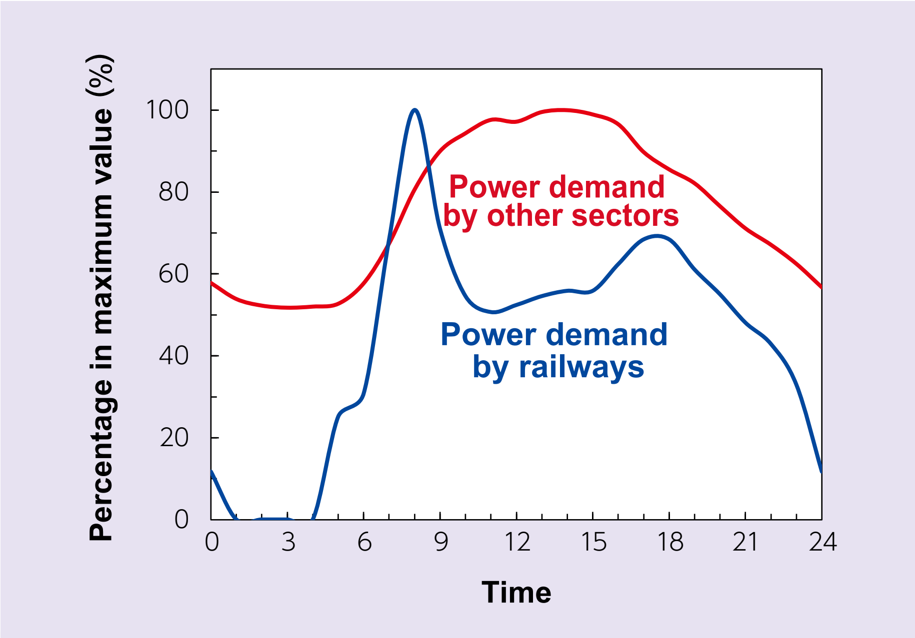
Let me ask you a candid question. In the longer term, the ratio of renewable energy in the commercial power grid is expected to increase and Japanese railways are already highly electrified. So, it seems that the carbon footprint of Japanese railways will be inevitably reduced in due course, is that right?

Shigeeda It's true that the power supply side roadmap shows that direction. However, if you are asking whether railways will be automatically decarbonized, that is not so simple. Railways' energy demand peaks in the morning and evening. So, in terms of leveling the peak, railways' energy consumption pattern matches well with the overall power demand that peaks during the daytime. (*Power demand fluctuation in a day*)

However, even if the daytime power supply amount is increased by a rising ratio of photovoltaic power, currently railways cannot use it effectively. It makes no difference, basically, whether we use the commercial power grid or private power generation.

So we need to adjust demand and supply by using energy storage systems, and the demand and supply adjustment function through the power exchange market has been gradually improved. However, it is still unclear whether the business can be commercially viable, and probably railway operators will have to watch carefully how the business develops before they make decisions to advance into the market.

Furukawa By 2024, a diverse lineup of the demand-supply adjustment products is likely to be introduced into the market. However, at this moment, the design of the entire adjustment system is still in progress. We will need to share information with other related organizations and keep watching their development closely.



Power demand fluctuation in a day

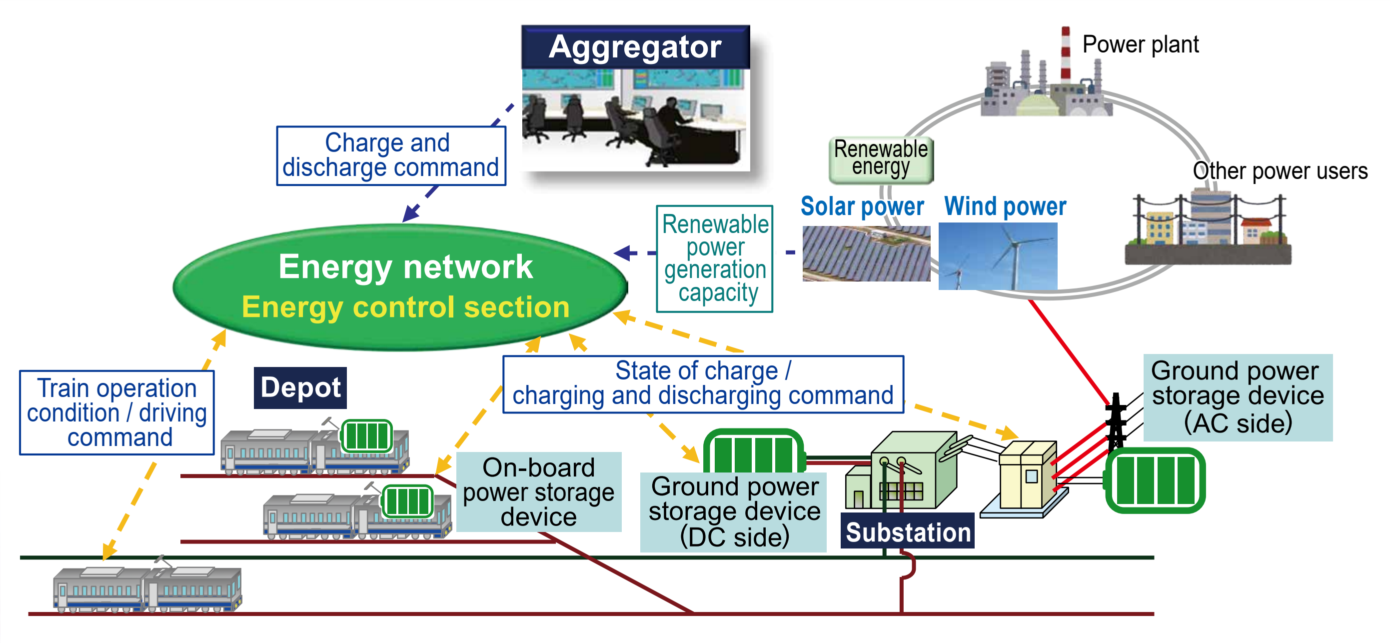
Research at RTRI toward decarbonization

Muramoto Now we are going to review RTRI's research and development to decarbonize railways. Table 1 lists R&D projects related to decarbonization that we have implemented in more than 20 years since the master plan "RESEARCH 21" started in 2000. Actually, we have completed 3 times as many projects, but are only showing representative and distinctive ones here. How do you evaluate these accomplishments?

Furukawa Frankly speaking, I have the impression that we have been doing well, and at the same time, I think we still have a long way to go. As I have said, railway people have been addressing the issue of energy saving for a long time and several projects have already been implemented. But until around 2015, the year that

R&D Projects at RTRI regarding Decarbonization

	RESEARCH 21 (FY2000 to 2004)	RESEARCH2005 (FY2005 to 2009)	RESEARCH2010 (FY2010 to 2014)	RESEARCH2020 (FY2015 to 2019)	RESEARCH2025 (FY2020 to 2024)
CO_2 Emission reduction	• Basic Research to use fuel cell as power source to run railway vehicles • Development of fuel cell system for railway vehicles	• Development of railway vehicles running on fuel cell • Research into geopoly-mer concrete	• Long-term deterioration characteristics of fuel cell • Development of geopolymer concrete and application to railway facilities	• Development of a power converter for fuel cell trains • Research into biomass as material for sleepers	• Development of a fuel cell hybrid train • Reduction of carbon emissions by fuel cell railway systems • Performance assessment of bio-fuel diesel engine
CO_2 Emission reduction and energy saving	• Development of systems for power-recycling vehicles • Power storage at substations	• Development of battery-powered vehicles using regenerated energy • Research into the control method for power storage device • Basic research into flywheel power storage device for railways using superconducting magnetic bearing • Research into supercon-ducting magnetic bearing for flywheel power storage device for railways	• Development of battery-catenary hybrid train for conventional AC-powered railway lines • Improving efficiency of flywheel for railways • Development of flywheel for railways using high-performance superconducting magnetic bearing	• Development of an assessment method for lithium-ion fuel cell degradation under the on-board conditions • Technical development to introduce flywheel for railways to commercial operation • Development of energy-network controlling method based upon predictions of energy consumption by vehicles and ground facilities	• Durability assessment of batteries to drive vehicles under highly frequent charging • Improving the charging and discharging performance of superconducting flywheel • A design method of compact superconducting flywheel requiring less maintenance • Development of basic technologies for supercon-ducting magnetic energy storage systems • Development of control method for smart power storage systems • Real-time coordinated energy control
Energy saving	• Development of traction transformer for train vehicles • Methods to reduce air resistance on railway vehicles and evaluation of them • Development of energy saving driving support systems • Research into reduction of energy consumption by changing parameters of traction circuit	• Development of the method to calculate energy consumption by railway vehicles	• Development of sophisticated rectifier • Building technologies to develop long-length superconducting feeding cable • Building a method to optimize vehicle structures to improve carbody strength • Proposal on building carbody using pressed shell • Evaluation of impacts of turbulence field on a railway train • Development of high-efficien-cy induction motor	• Development of high-perfor-mance power converter for high-voltage power supply • Development of element technologies to introduce superconducting feeding cable to railway operation • Development of supercon-ducting power supply systems • Evaluation of energy-saving effects using advanced train operation power simulator • Design method for disc-type motor	• Kilometer-class superconduct-ing power supply systems • Building technologies to connect components in superconducting power supply systems • Development of real-time energy-saving driving techniques • Development of energy-saving train timetable considering passenger convenience • Development of the method to estimate energy consumption by freight trains • Development of disc-type direct driving motor
Promoting modal shift to railways	• Ride comfort evaluation of tilting trains and research into technologies to improve ride comfort • Development of intelligent truck for high-speed running on curves • Development of low-cost semi-active vibration control device for Shinkansen • Analysis of carbody elastic vibrations and research into vibration reducing techniques • Research into sources of cabin noise and methods to prevent noise transmission • Analysis of sickness-in-ducing factors on a swaying train and research into mitigating techniques • Development of ride comfort assessment methods	• Development of carbody vibration control systems with controlled axle damper • Development of vertical vibration control systems with variable axle damper • Research into evaluation and improvement of carbody damping performance • Research into assess-ment methods for station and cabin conditions from passengers' viewpoint • Assessment of combined impacts of vibrations and low-frequency noise on high-speed trains on passengers	• Development of carbody tilting and steering technologies to conventional trains' speed increase • Development of running gear for commercial services meeting both desirable curve-negotiat-ing speed and ride comfort • Research into technolo-gies to improve ride comfort in different running modes • Methods to model and reduce carbody elastic vibrations considering different running modes • Research into ride comfort based upon characteris-tics of human sensitivities to vibration and noise • Building a prediction model for ride comfort in changing temperatures	• Development of carbody tilting system to improve ride comfort • Development to extend use of vertical-vibration damper and to improve its performance • Improving ride comfort by insulating longitudinal vibration between truck and carbody	• Improving performance of tilting-control system corresponding to high-speed running on curves • Development of low-cost integrated vertical-vibration damping system • Promoting commercial use of cabin-noise reducing technologies based upon noise transmission characteristics • Assessment method for comfortable cabin temperatures under sunlight • Assessment method for the comfort level of air-condi-tioned cabin using feeling-temperature prediction model



Smart power storage system

"RESEARCH 2020" started, reduction of carbon footprint had not been such a hot topic in society. So, most of the projects shown in the table were mainly aiming at energy saving, improving ride comfort and speed increase, and they were not directly targeted at decarbonization. To be honest, I would say, we restarted our effort to pursue decarbonization and net-zero, when our new master plan RESEARCH 2025 was launched.

But it is true that having accumulated these research experiences and outcomes gives us a great advantage. We would like to accelerate new projects based on the expertise we have developed so far.

Muramoto In this table, we can recognize that RTRI had already started to develop a fuel cell for railways and the energy storage system at a substation under the RESEARCH 21 started in 2000. We are still working on the development of a fuel cell vehicle. How about the energy storage at substations?

Shigeeda In those days, we were exploring a energy storage system to save energy by efficiently using regenerative power. Since that system is required to repeat charge and discharge cycles frequently, depending on acceleration and deceleration of trains, we developed a energy storage system using an electric double-layer capacitor. This device was expected to have shorter response time and longer service life than other rechargeable batteries. Later on, the performance of the lithium-ion battery was improved significantly and became the mainstream energy storage cell. But we have gained extensive expertise on device controlling through the development of energy storage system. We have shifted our research target to the energy management system and currently are developing technologies to store renewable energy in order to enhance values of energy storage system. We have used our expertise, such as in control methods, to store renewable energy in this system.

Muramoto So, you are saying that, regarding the hardware like batteries, RTRI will choose the best products of the time, devices of excellent cost performance, and pursue the efficient management of them in railway operation.

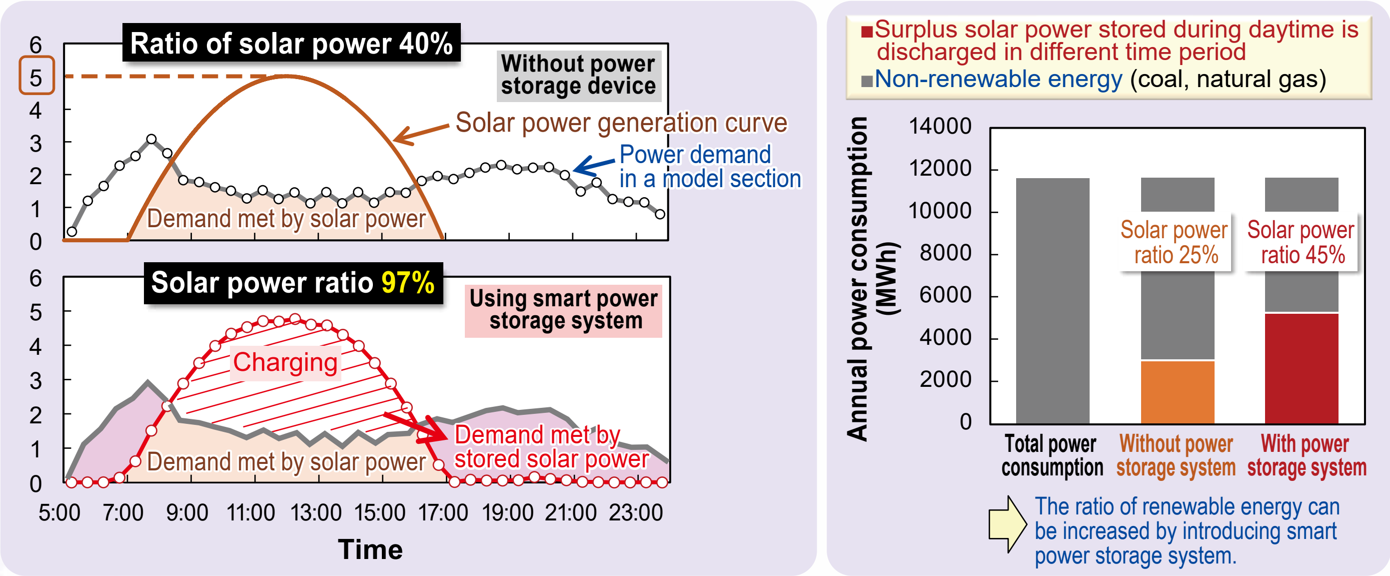
Achievement of net-zero in 2050

Muramoto Please talk about the prospect of RTRI's research and development of the achievement of net-zero in 2050.

Shigeeda In addition to the target year 2050, we also need to address the current task of 46% reduction (from 2013) of greenhouse gas emissions including CO_2 by 2030. As I mentioned earlier, the use of renewable energy cannot be increased without adjusting demand and supply balance. RTRI has set "reducing carbon footprint by coordinated power control in power supply network" as one of the major research targets in RESEARCH 2025. As one of the projects in this field, I would like to introduce our smart energy storage system to promote energy saving and use of renewable energy in the railway power supply systems. (*Smart power storage system*)

Shigeeda *"Increasing solar power ratio by smart power storage system"* shows an example of the power supply patterns for a model line calculated by the train operation power supply simulator that we have developed. During daytime, the electricity from photovoltaic power generation exceeds the amount consumed in railway operation. The surplus is stored and discharged in the morning and evening to meet the peak-hour demand by railways. In the simulation, if the photovoltaic generationplant's capacity can cover the entire power demand for one railway line for a day and the energy storage device is capable of storing the entire amount of the power, 97% of the power necessary for train operation can be covered by photovoltaic power alone in the summertime, when the photovoltaic power amount is highest. The annual average ratio also reaches 45%. In the smart energy storage system, train-equipped energy storage devices share the role with the devices at substations.

Shigeeda And, in order to finally attain the goal by 2050, it will be essential to develop high-performance, large-capacity energy storage system for commercial use. RTRI will continue to develop toward commercial use the Flywheel-type energy storage system using the super-conducting technologies that RTRI has accumulated. Furthermore, we have undertaken the development to use the superconducting magnetic energy storage (SMES) for railway operation based on the expertise we have gained in developing a super-conducting power supply cable, which is getting closer to commercial use.



Increasing solar power ratio by smart power storage system

Furukawa It was in 1970's, at the time of the so-called oil shock, that the concept of energy saving was widely recognized for the first time in Japan. So, until recently, the phrase "energy saving" has meant reduction of fossil energy consumption. Most recently, however, it has started to also imply raising the ratio of non-fossil energy toward the achievement of net-zero, and I hear the government is working on the revision of the energy-saving law (Law concerning the Rational Use of Energy) in that perspective. We are going to further improve the systems and technologies to use renewable energy for railway operation by continuing to develop the smart energy storage system. In addition, we will address carbon footprint reduction by developing other technologies as well. We will develop fuel cell vehicles and battery trains to decarbonize non-electrified train lines, and technologies to use biofuels to run diesel vehicles.

However, fierce battles for biofuels are expected among industrial sectors and it will be increasingly difficult to obtain rare metals including lithium, which is used for batteries. So we will need to keep an eye on broad-ranging technical fields in medium- and long-term perspectives, without narrowing our research possibilities.

Furukawa In the longer term, all of our research and development projects will be evaluated based on whether they can contribute to attaining a sustainable society or not. So far cost performance has been the first priority in introducing research outcomes to commercial use. But going forward, we may have to make clear evaluations on whether the technologies can contribute to decarbonization or not. Currently, for example, construction methods using cement and concrete components are prevailing. But cement and concrete components emit a large amount of carbon dioxide when they are produced. So, it may not be long before we can have alternatives of using lower-carbon or carbon-recycling materials and construction methods such as geopolymer. But after all, everything, including CO_2 emissions, needs to be calculated into cost. So, regarding the overall cost reduction, the Materials Technology Division will be playing a major role in the research to keep the entire cost at a reasonable level.

As we mentioned earlier, we are seeking to reduce the greenhouse gas emissions by 46% in 2030, as a midterm goal to attain net-zero by 2050. The projects started under the current master plan RESEARCH 2025 which contribute to decarbonization will be continued under the next master plan (fiscal 2025 to 2029). We will continue the research and development in cooperation with divisions at RTRI and other organizations ranging over different fields and sectors in order to create outcomes contributing to the goal of CO_2 reduction in 2030.

Muramoto Dr. Furukawa, Dr. Shigeeda, thank you for being with us today.

High-Performance Compact Traction System of Fuel Cell Hybrid Powered Test Railway Vehicle

Mr. Takayuki Kashiwagi
Senior Chief Researcher
Hydrogen and Sustainable Energy Laboratory

RTRI has been developing an energy-efficient fuel cell hybrid powered railway vehicle with low carbon-dioxide emissions in an effort to address global environmental issues. We have examined the possibility of replacing DMUs with fuel cell hybrid powered railway vehicles. In 2019 we downsized and improved the performance of the fuel cell hybrid powered railway vehicle's traction system, seeking to replace not only DMUs but also part of EMUs. This development has made it possible to install all the equipment for running underfloor, achieve high acceleration performance equivalent to an EMU, and secure sufficient cabin space. This article explains the development of the fuel cell powered hybrid test vehicle.

Introduction

In recent years, driving systems of automobile have been rapidly shifting from conventional gasoline engines to electric motor and gasoline engine hybrid systems to reduce carbon footprint and energy consumption. While Japanese railway vehicles have been mainly EMUs in urban areas, mostly DMUs are running in rural, non-electrified areas. This is because the ground facilities for DMUs are simple and less expensive compared to electric power supply facilities. However, due to the urgent necessity to conserve the global environment, DMUs have been replaced either with hybrid diesel vehicles driven by both electric motor and diesel engine or with battery vehicles. These vehicles have their drawbacks and advantages in terms of environmental impacts and cruising distance. Since 2001, RTRI has been developing a fuel cell hybrid powered test railway vehicle satisfying both requirements. This article describes our development to downsize and improve the performance of the driving system of the fuel cell hybrid powered test railway vehicle, targeting replacement of not only DMUs but also part of EMUs.

Fuel cell

Among several types of fuel cells, the polymer electrolyte fuel cell, which is called PEFC, is used for railway vehicles. This fuel cell generates electricity by reacting hydrogen as fuel with oxygen in the air. This type of fuel cell has the advantages that it has shorter start-up time compared to other fuel cells, higher energy efficiency than diesel engines, and that it is a clean device as it emits only water when it generates electrical power.

Fuel cell hybrid powered railway vehicle

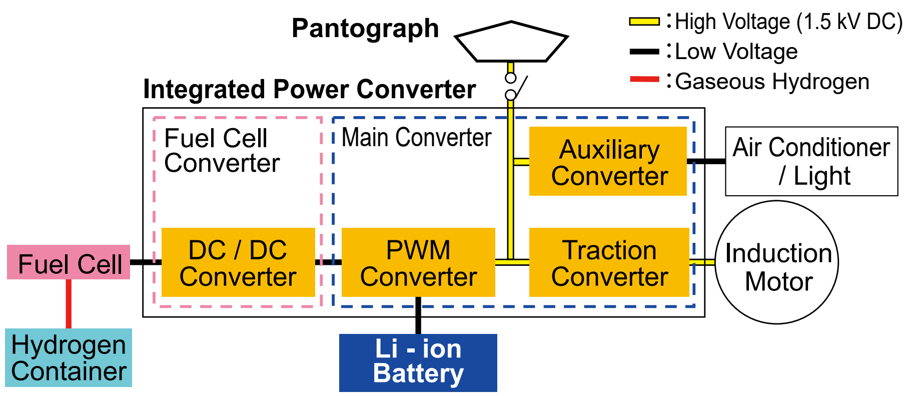
The hybrid powered railway vehicle combines a fuel cell and a battery for its power source and use electricity efficiently to drive (*Traction system of a fuel cell hybrid powered test railway vehicle*). During accelerating, both the fuel cell and the battery provide electricity to motors. During coasting, the fuel cell charges the battery, and during braking, regenerated power and the fuel cell charge the battery.

Downsizing and improving performance

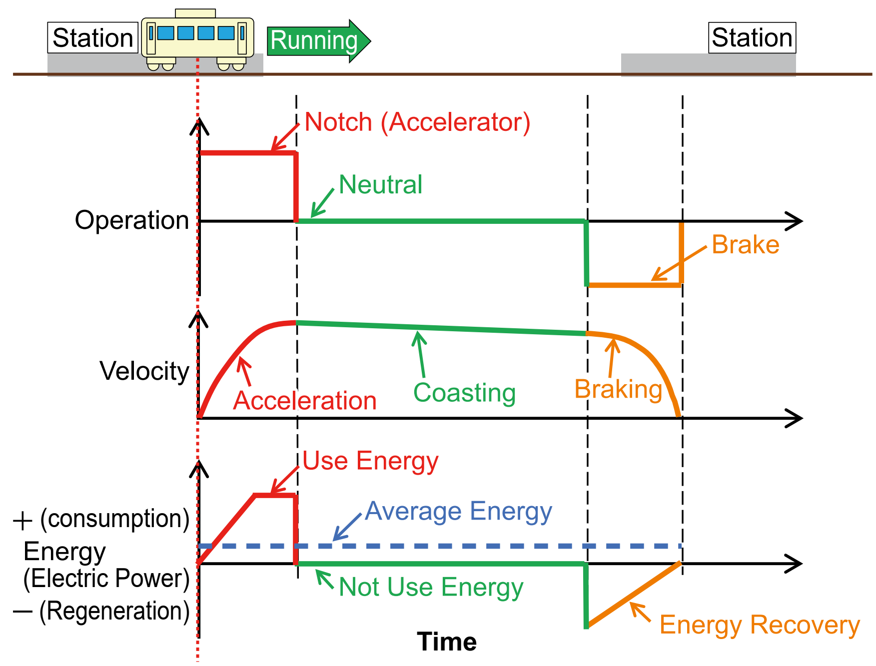
In the initial stage of developing the fuel cell hybrid powered test railway vehicle, RTRI focused on research and development for using fuel cells as a part of traction systems for railway vehicles and has continued running tests for more than 10 years. However, the performance of the fuel cell and the battery was limited. Also, the equipment for running was large and was placed in the cabin. Due to the size and performance, sufficient space for passengers was not available and the acceleration performance remained at the level of the old-type DMU (0.4 m/s^2). To address these challenges as the next step, RTRI started to develop a vehicle which has sufficient cabin space and enough acceleration performance equivalent to an EMU (0.7 m/s^2 or higher). If vehicles with these performances are developed, we can replace DMUs running on non-electrified lines with them and reduce CO_2 emissions. Furthermore, if vehicles running on electrified but lower-traffic lines are replaced with the hybrid vehicles, the ground power supply facilities can be reduced, and maintenance cost can be cut without compromising the quality of passenger services such as travel time. The targets of research to attain this goal are explained in the following paragraphs.

Calculation of power output of fuel cell and battery

Since a fuel cell has only limited output per volume and is very expensive, it is not reasonable for the fuel cell to provide all the necessary power of vehicle operation. Power consumption by conventional railway trains has a characteristic pattern. The trains use large power during acceleration, but the average power thorough entire running time is lower than the maximum power for acceleration (*Example of a conventional railway vehicle power usage*). Regenerative power during braking recovers a part of the power used for the acceleration. To take this characteristic into account, the fuel cell is designed to have the output equivalent to the average amount of power loss during running. Meanwhile, the battery output covers the difference between the power demand for running and the fuel cell output. This reduces the size and cost of the fuel cell. Under this design policy, we simulated a two-car trainset running over a short, flat section with the acceleration performance equivalent to an EMU (0.7 m/s^2) and examined the desirable output of equipment. Based upon the result of this research, we have determined fuel cell output to be 150 kW and battery output to be 540 kW and designed each equipment to be manufactured according to this specification.



Traction system of a fuel cell hybrid powered test railway vehicle



Example of a conventional railway vehicle power usage

Downsizing and improving performance of fuel cell

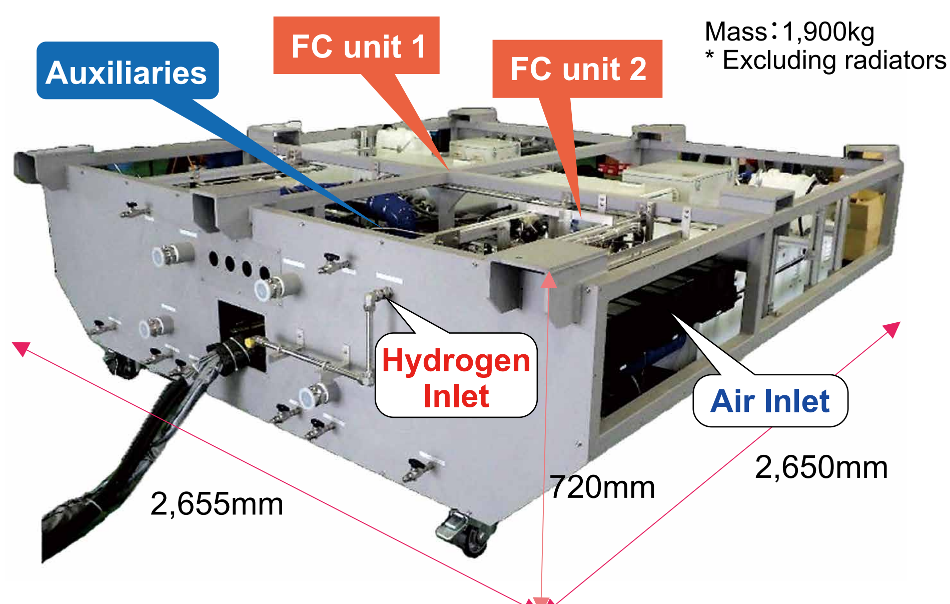
It was necessary to raise the output of the fuel cell 1.5 times higher than existing equipment and downsize them so they can be mounted to the underfloor of the vehicle. The fuel cell has many components including fuel cell stacks, device to take in air to react with hydrogen, and cooling device to dissipate heat from power generation. Therefore, in addition to raising power generation performance of the fuel cell stacks, we downsized the cooling device by making its design simpler. We have succeeded in increasing the output by 50% and reducing volume per output by 23% by downsizing peripheral equipment (*Comparison of fuel cell unit*). With these improvements, we developed a thinner fuel cell that can be mounted under a vehicle's floor.

Comparison of fuel cell unit (Former one equals 1)

Items	Former Fuel Cell Unit	Downsizing Fuel Cell Unit
Output	1	1.5
Output per Volume	1	0.77

Downsizing power converter

Traction system of a fuel cell hybrid powered test railway vehicle shows a schematic diagram of the power converter. Since the input voltage of the traction converter and auxiliary converter is set at 1500 V in this circuit, the voltage used in most DC-powered sections in Japan, the fuel cell railway vehicle can run as EMUs powered by an overhead power supply line without using the fuel cell. As the railway vehicle does not use hydrogen in the electrified sections, cruising distances in non-electrified sections can be extended. This circuit has a set of two fuel cells and a set of three batteries connected to each converter, so the railway vehicle can keep running even if one of the fuel cells or the batteries fails, thereby improving reliability. The number of overlapping components in this circuit has been reduced by integrating converters for traction, auxiliary power and



Exterior of the fuel cell

Exterior of the power converters

(a) Main converter

(b) Fuel cell converter

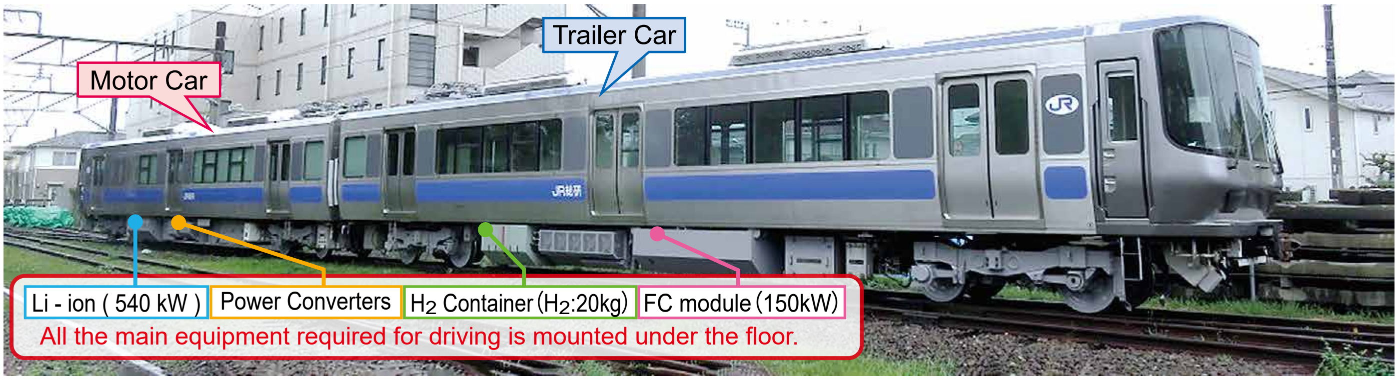
Comparison of power converters (Former one equals 1)

Items	Former Power Converters	Downsizing Power Converters
Volume	1	0.55
Weight	1	0.6

batteries, allowing a smaller main converter to be configured. Since the voltage of the fuel cell converter has been reduced by improving the circuit configuration and a low-loss SiC power device was used, the cooling device was downsized and smaller-sized circuit breakers were used. These improvements made downsizing the entire fuel cell converter possible. The volume and weight were reduced by 45% and 40% respectively compared to the previous power converter (*Comparison of power converters*).

Test vehicle and running test results

The traction system of the fuel cell hybrid test vehicle was downsized and its performance was improved. *Exterior of the fuel cell hybrid powered test railway vehicle* shows the improved test railway vehicle, and *Comparison of cabin* shows the cabins of the previous railway vehicle and the improved one. Tests to confirm running performance were conducted with this improved test railway vehicle



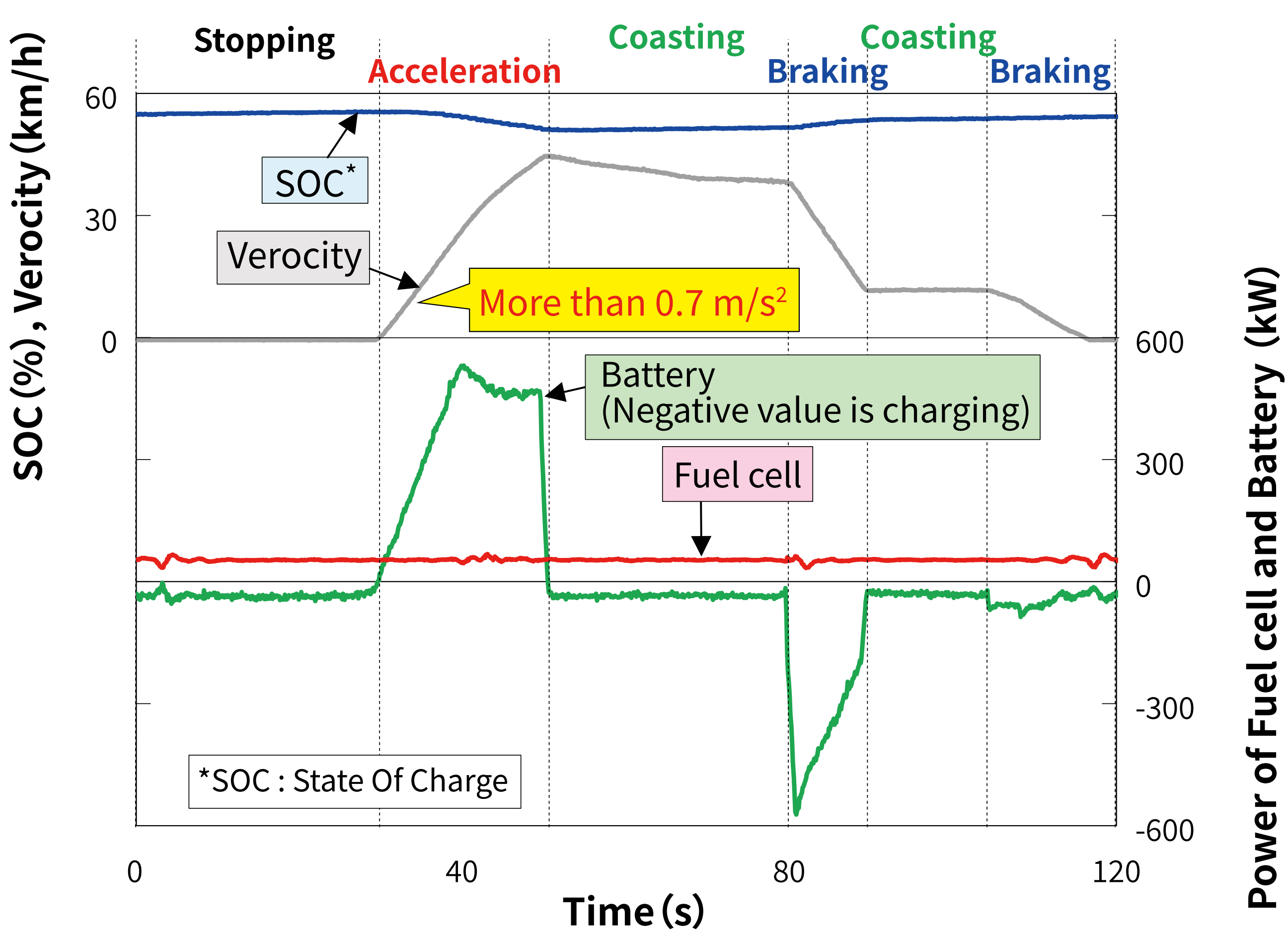
Exterior of the fuel cell hybrid powered test railway vehicle

on the 650-meter test track at RTRI. The test railway vehicle attained a starting acceleration of 0.81 m/s^2 (0.78 m/s^2 before slope adjustment), which confirms it has an acceleration performance equivalent to an EMU (*A test result on the test track*). Furthermore, as almost the same levels of battery SOC (State of charge) have been shown before and after the test running, we demonstrated that the energy used for running has been compensated by charging from the fuel cell as designed and the railway vehicle can run continuously.

Conclusion

The fuel cell hybrid powered test railway vehicle features high energy efficiency and a low carbon footprint, and we can conclude that it is one embodiment of what a railway vehicle should be in the future. In the meantime, the hybrid powered railway vehicle still has a long way to go before it is introduced to revenue service. In addition to further development of the vehicle, laws and regulations are

Comparison of cabin



A test result on the test track

required, such as a high-pressure gas security act that will enable railways to safely use high-pressure hydrogen gas. A hydrogen supply chain needs to be built as large amounts of hydrogen will be needed and the currently expensive cost of the fuel cell must be reduced. We expect that these issues will be solved as the energy source for our society further shifts to hydrogen, and the fuel cell hybrid powered railway vehicle will be used widely. At the same time, we hope the hybrid powered railway vehicle we have introduced here which has a small-sized, high-performance traction system will help the social change.

A part of this work was financially supported by the Japanese Ministry of Land, Infrastructure, Transport and Tourism.

Reducing Loss in Railway Power Supply by using Superconducting Technologies

Superconducting technologies to save energy include superconducting feeder cables for power transmission and superconducting magnetic energy storage systems. In this article, I will introduce the superconducting feeder cable used for railway power transmission. Since a superconducting cable has no electrical resistance, it can help save energy by reducing power loss in transmission and reduce the number of substations by preventing voltage drop. RTRI has already conducted running tests to check the power supply performance for railways using superconducting feeder cables.

Dr. Masaru Tomita
Director
Maglev Systems Technology Division

Superconducting technologies for railway operation

Category	Superconducting technologies
Power supply	Superconducting feeder cable*, Superconducting transformer, Superconducting Magnetic Energy Storage*, Current lead, Fault current limiter
Magnetic field application	Superconducting magnetically levitated train system, Superconducting motor, Superconducting magnetic bearing

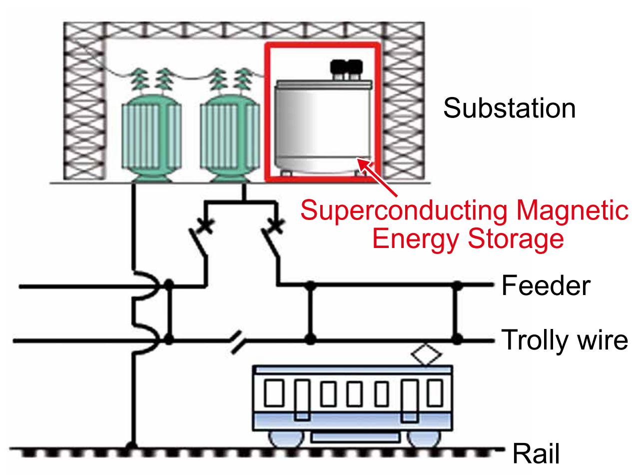
* : Technologies mainly for energy saving

Introduction

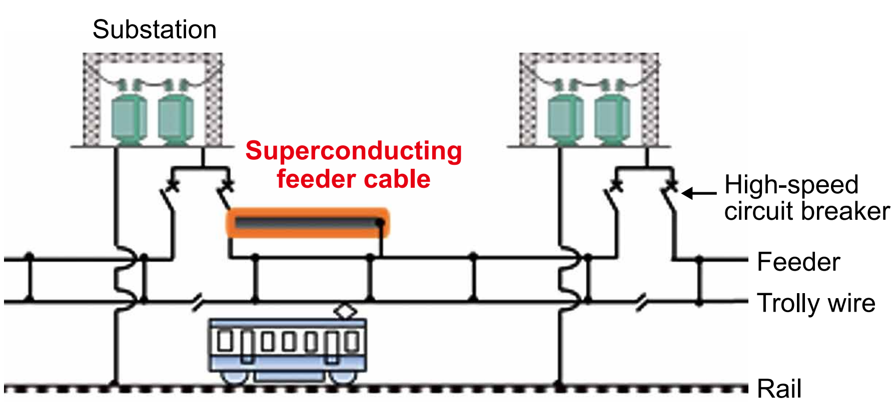
The energy loss in power transmission for railway operation is approximately 5%. This means a vast amount of energy is lost in railway operation worldwide. In railway operation, power transmission technologies play an important role, and we still have a lot to do to improve them to further save energy consumption. Superconducting technologies for railways have already been applied to the transformer, current lead, and fault current limiter in power supply systems. As examples of using magnetic field, superconducting magnetically levitated train systems and motors using magnetic field are being developed (*Superconducting technologies for railway operation*). Among them, superconducting magnetic energy storage and superconducting feeder cables can save energy by reducing power supply loss. These technologies will be explained in this article.

Superconducting magnetic energy storage

In operating electric railways, power storage devices have been drawing attention because regeneration rate can be improved and power load can be leveled with this technology. However, as the lithium ion battery, a commonly used energy-storage device, has a problem in quick charging, we are developing a Superconducting Magnetic Energy Storage (SMES) capable of rapid charging and discharging (*SMES introduced to a feeding system*). The SMES stores electricity as magnetism directly in the coil made of superconducting wire. This device enables electricity to flow without power loss because the coil has zero electric resistance. This means it will enable instant charging and discharging if necessary. While a lithium ion battery stores electric energy as chemical energy, the SMES stores it directly as electric energy and has high efficiency, longer service life and higher input and output. As the depletion of helium is becoming an increasingly serious issue, we are developing a next-generation superconducting coil using magnesium diboride (MgB_2) wire which does not need liquid helium for cooling[1]. Since a MgB_2 coil can be cooled only by heat conduction from a cryocooler, it does not need any refrigerant. In addition, as liquid hydrogen can be used for cooling a MgB_2 coil, the coil will fit into the future hydrogen-based society with zero carbon footprint.



SMES introduced to a feeding system



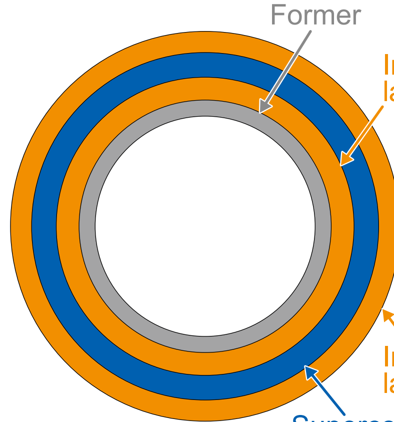
Superconducting feeder cable introduced to a feeding system (Connecting part of substations)

Development of superconducting feeder cable

Next, I would like to explain our development of feeder cable using superconducting technologies. Japanese railway lines contain a large number of DC electrified sections and have the energy loss problem stated in the Introduction. European high-speed railways also have the same problem, since urban rail lines in Europe are DC electrified. Superconducting power transmission is highly expected at home and abroad to solve issues of power loss and voltage drop and to improve running stability. In this context, we have been developing technologies to reduce power transmission loss by using superconducting feeder cable for the next-

Analysis of energy-saving effects by introducing superconducting feeding system

	Required energy [kW]		
	Power output at substation	Cooling energy	Total
Superconducting feeding system	9,080	1,238	10,318 (95)
Existing feeding system	10,856	-	10,856 (100)



Cross-section view of superconducting cable core

generation railway systems.

In this development, we have completed material testing and reviewed the system design. Now we are in the phase of confirmation testing on RTRI's test track and commercial lines[2].

Initial model of superconducting feeder cable

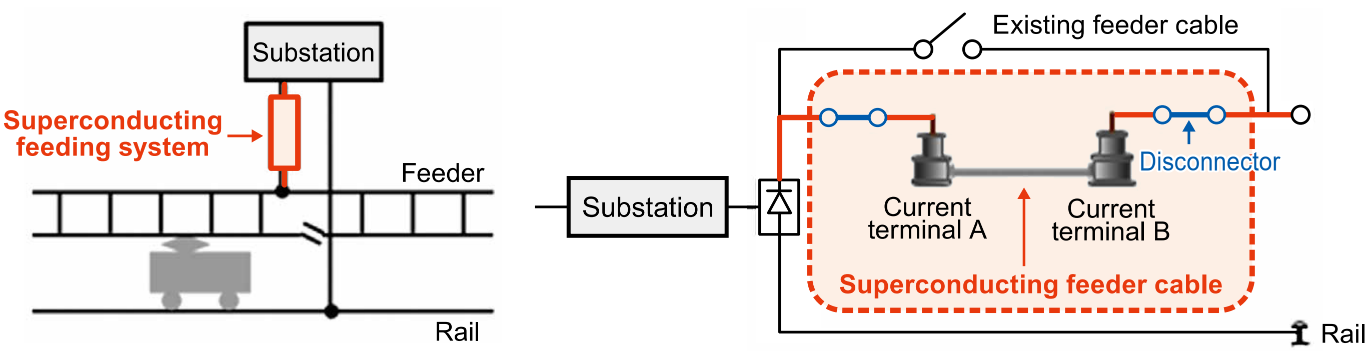
Superconducting feeder cable introduced to a feeding system (Connecting part of substations) shows a schematic of the superconducting feeder cable used in a railway power supply system. In this example, the superconducting cable is connected part of substations to prevent voltage drop that takes place in some sections between substations. The superconducting cable can be introduced to feeding systems in several patterns, depending on conditions. The cable can be connected either an entire section or part of it between substations, or a feeding branch device can be placed between the regular feeder cable and superconducting one. If the whole section between substations is connected with superconducting cable, voltage drop can be reduced. Furthermore, by feeding power from each substation, the maximum current at substations can be reduced and power load between substations can be leveled. It is also possible to transmit regenerated power to distant trains.

To assess the effects of introducing superconducting feeder cables, we have analyzed the energy-saving effects of a system that connects substations with superconducting cable in parallel with regular feeder cable[3]. The results of the analysis are shown in Analysis of energy-saving effects by introducing superconducting feeding system. If superconducting feeder cable is introduced to a conventional railway line, required daily energy is reduced approximately 5%, from 10,856 kW to 10,318 kW (*Analysis of energy-saving effects by introducing superconducting feeding system*).

Testing of superconducting feeder cable

As shown in *Cross-section view of superconducting cable core*, superconducting cable is made by winding superconducting tape and insulating paper around the core part. The former is a pipe to wind other materials around. Superconducting tape is made of high-temperature superconducting material to conduct electricity and the insulating paper has a high dielectric withstanding voltage property. As the superconducting tape is subject to mechanical stress when being wound, tests have been conducted to assess how much current can be conducted through the tape when it is bent. As the amount of current passing through superconducting tape fluctuates due to the magnetic field caused by the tape itself, we are also conducting current tests under magnetic fields. Through these tests, we have determined the design policy for manufacturing superconducting cable.

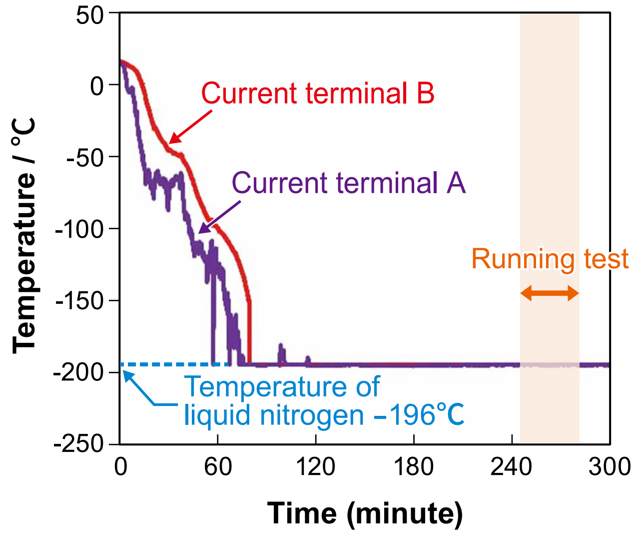
In the next phase, train running tests were conducted on a track equipped with superconducting cable for the purpose of basic technical confirmation in commercial line. Connections to actual commercial feeding systems and system operation were confirmed here[4]. In the running tests, we evaluated whether power loss occurs when the current through the superconducting cable is rapidly changed by notching to accelerate and decelerate a train. We have used a 6-meter-long superconducting cable and set the voltage at 1,500 V and current at 2,000 A. The superconducting cable was placed between the power output cable from a substation and an input point to a feeder. We set a simple circuit using the superconducting cable as shown in *Schematic circuit diagram*. A current terminal was placed at each end of the superconducting cable. In this test system, the existing feeder circuit can be shifted to a superconducting feeder circuit by switching a disconnector on and off. *Superconducting feeder cable connected to a track* shows the superconducting cable and the test train. The cable is cooled



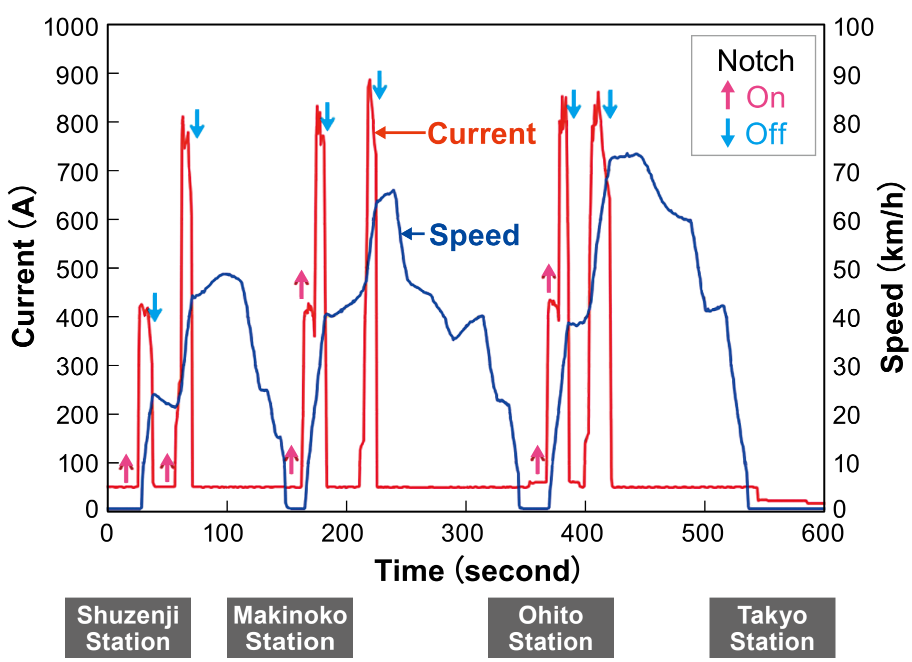
Schematic circuit diagram

Superconducting feeder cable connected to a track

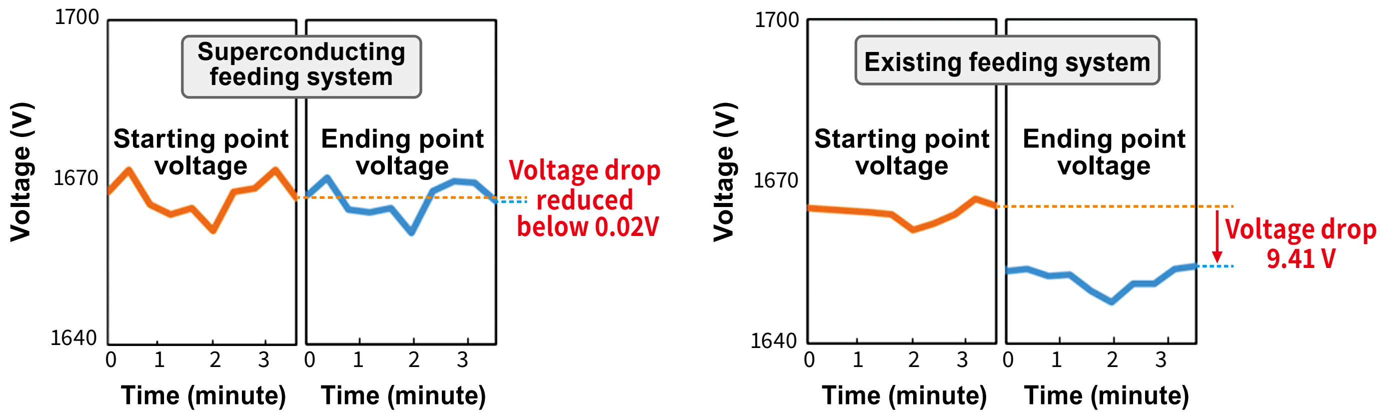
by immersion cooling with liquid nitrogen. *Temperatures of superconducting feeding system* shows the results of cooling by filling with liquid nitrogen from terminal B to A. We can see that the two terminals were cooled down to the liquid nitrogen temperature and initial cooling was completed in 80minutes after the filling started. After cooling, train running tests were conducted, and the current and train speeds were recorded by a vehicle-mounted recording device. The results are shown in *Results of test running with superconducting feeder cable*. A maximum 880 A current was supplied via the superconducting cable to the 3-car test train running the 5.6 km between Takyo and Shuzenji stations. The test running was successful. Although the cable current



Temperatures of superconducting feeding system



Results of test running with superconducting feeder cable



Voltage drop under superconducting and existing feeding

fluctuates significantly due to notching to stop and start trains, system temperature does not fluctuate (*Temperatures of superconducting feeding system*) and it was confirmed that power loss did not occur.

Next, we conducted power feeding tests using a 408-meter-long superconducting feeding system to examine its energy-saving effects. The capacity was set at 12 MW (8000 A, 1,500 V) to fit the capacity of the test track. The superconducting system was connected along the track in parallel with the existing feeder and the power was transmitted from a substation to a depot via the superconducting cable. 1,250 A current was flowed to ten 10-car trainsets in the depot for air-conditioning and lighting of all the vehicles. When feeding with the superconducting feeding system, the voltage is almost same level at the start and end points, and voltage drop was confirmed to be reduced to 0.02 V compared to 9.41 V measured when feeding with the existing cable (*Voltage drop under superconducting and existing feeding*). It was confirmed that power loss in superconducting feeding can be reduced about 7 kW for this 408-meter section.

Conclusion

Based upon these testing results, we will continue power feeding simulations targeting actual train lines and choose appropriate lines to introduce the superconducting feeding system. We are also examining the possibility of a long-distance system to be used for transmission between substations. We will keep developing superconducting feeder cables that can be applied to commercial railway lines.

Part of this project has been supported by the subsidy for railway technical development by the Ministry of Land, Infrastructure, Transport and Tourism, a research initiative “Superconducting Technology Innovation Creating the Next-Generation Railway Systems” by the Japan Science and Technology Agency (JST) and the Advanced Low Carbon Technology Research and Development Program (ALCA).

Predicting Energy-Saving Effects with the Train Operation Power Simulator

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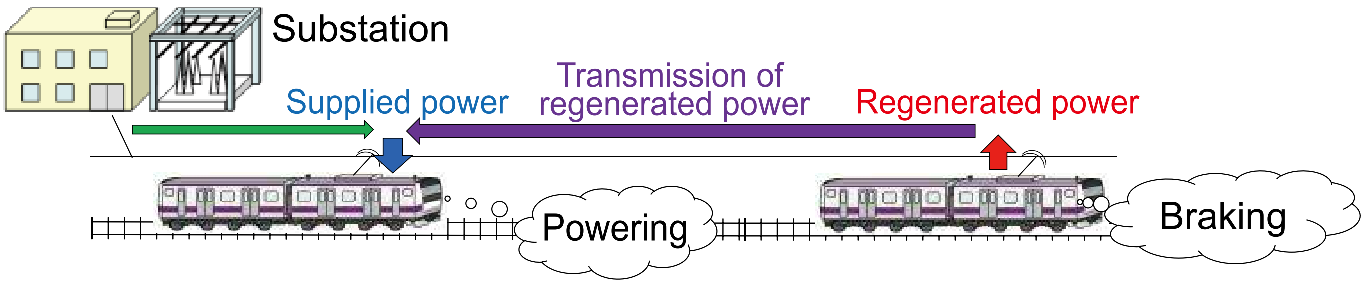
RTRI developed the Train Operation Power Simulator to calculate energy consumption by DC-fed train operation and predict the effects of energy-saving technologies for railways. This simulator closely reproduces average-realistic train driving profiles based on statistical data and train timetables. The results have been verified in terms of energy consumption for air-conditioning corresponding to outdoor temperatures. By considering important factors, we have used this simulator to examine the effects of energy-saving technologies for railways. This article describes examples of predicting energy-saving effects by introducing energy storage systems and energy-saving trains.

Introduction

Since the trains of electrified railways are operated with the electric power supplied via overhead contact line systems (OCS) or third rails, railway operators have been implementing measures to reduce energy consumption in train operations. One of the major efforts is to introduce onboard traction control system with regenerative brake function. During regenerative braking, motors are used as power generators when the brakes are applied, and the generated power is sent back to contact lines. In recent years, a variety of energy-saving technologies have been developed to use regenerative braking efficiently. In addition to regenerative braking, railway operators have changed improved the efficiency of on-board devices and/or the configuration of power supply facilities to reduce electrical resistance.

Given a limited budget, it is necessary to choose efficient measures among these energy-saving technologies. However, the cost-effectiveness varies depending on the technologies. The difficulty in introducing energy-saving technologies is that the effects vary depending on the locations of power supply facilities and the features of the lines. If technologies with the same specifications are introduced, more efficient ways of introduction are required. And, as is explained later, if higher-performance new vehicles are introduced to revenue services, it is possible to shorten running time as well as to save energy. Thus, it will also be important to examine the effects from different viewpoints as well as energy-saving when predicting the effects of



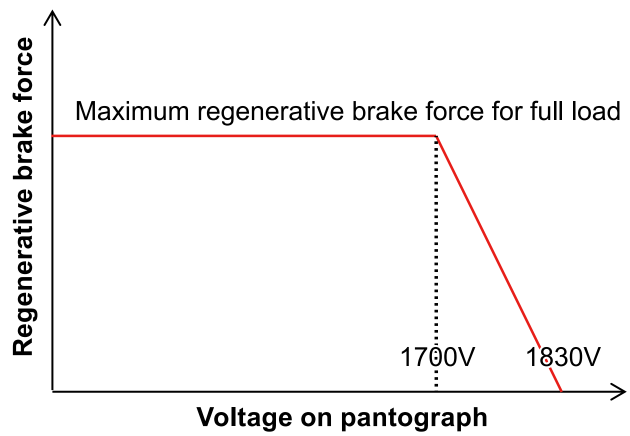
Transmission of regenerated power

introducing energy-saving technologies. For this purpose, RTRI developed the Train Operation Power Simulator to predict the energy consumption by the operation of a large number of trains in wide areas. This article explains the energy-saving technology with regenerative braking and describes the mechanism of the Train Operation Power Simulator with examples of predicting the effects of introducing energy-saving technologies.

Energy-saving technologies with regenerative braking

Transmission of regenerated power shows the power generated by regenerative braking is sent back to contact lines and used effectively by another train running close by. However, if other trains are not close by or braking is required according to geographical conditions such as curves and slopes, regenerative braking cannot be used effectively. Generally DC-fed trains have function of reducing regenerative brake effort as shown in *Controlling restriction of regenerative braking* not to exceed the limit of the maximum contact line voltage and mechanical brake takes the required braking effort over. Further energy-saving will be attained by avoiding such regenerative brake force reduction.

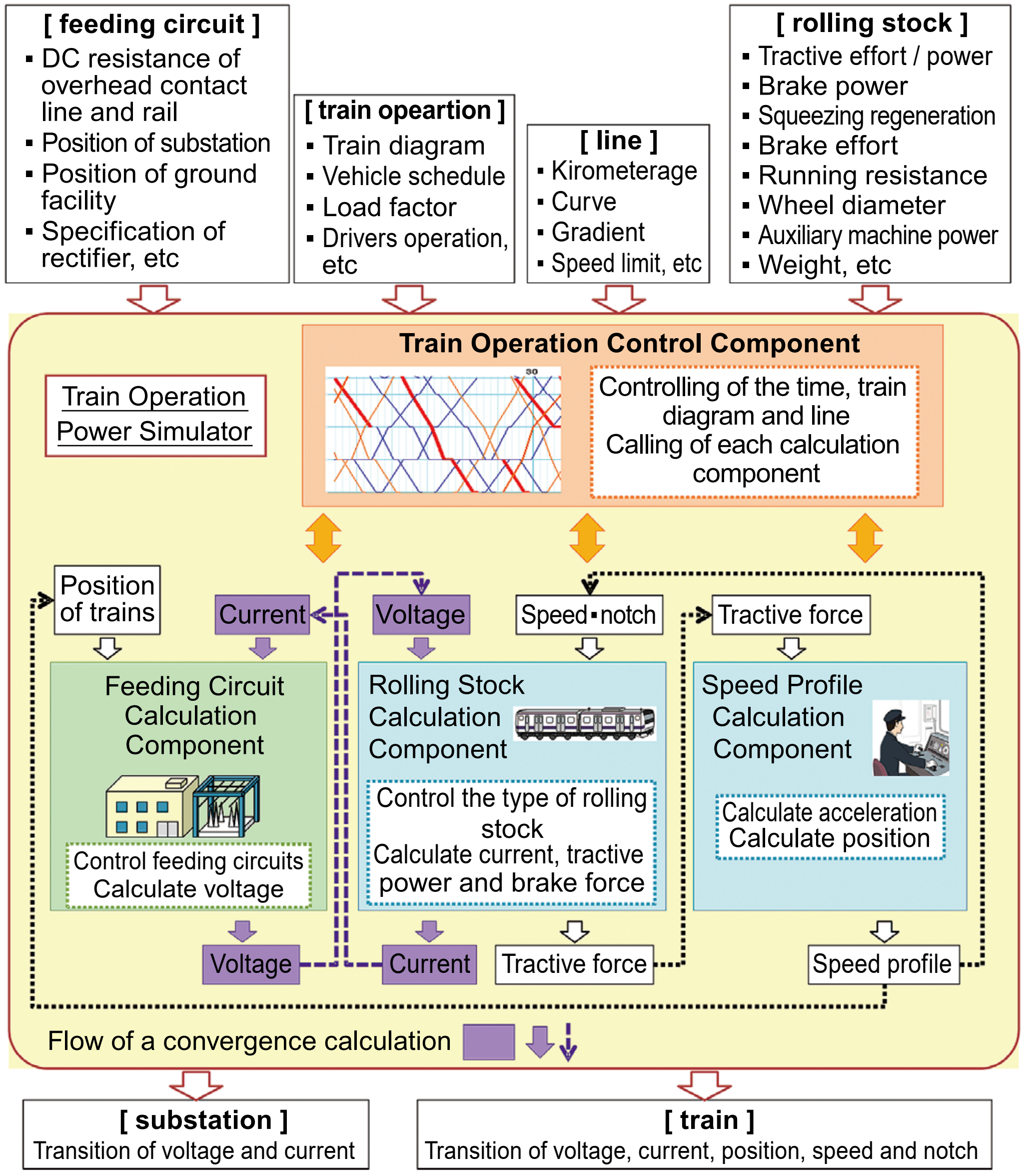
Among the efforts to improve the effectiveness of regenerative braking, some railway operators have installed stationary energy storage systems to reuse the energy in or regenerative inverters to send regenerated power at auxiliaries such as escalators and lighting in stations. The Train Operation Power Simulator has been developed with particular focus on controlling power regeneration and is capable of predicting the effects of energy-saving technologies.



Controlling restriction of regenerative braking

Mechanism of Train Operation Power Simulator

The Train Operation Power Simulator simulates train operation of DC railways and calculates energy consumption (*Functions and configuration of Train Operation Power Simulator*)[1]. Its train operation control component calls a calculation program to start trains according to a train timetable. The speed profile calculation component develops speed profiles for the operating trains. The component solves the equation of motion with the tractive force calculated by the rolling stock calculation component. It determines the driving status of the train among powering, coasting, or braking, and develops speed profiles. The tractive force varies depending on the catenary voltage and is calculated by the feeding circuit



Functions and configuration of Train Operation Power Simulator

calculation component. Catenary voltage is calculated by solving the equation of the feeding circuit, but changes depending upon train positions, that is, train timetable and speed profile. It means that catenary voltage, tractive force, and speed profile depend on one another. The speed profile is recalculated at each time step based on the catenary voltage.

One of the functions of the Train Operation Power Simulator is to provide speed profiles for energy consumption estimation (*Creating a speed profile for energy consumption estimation*). Since speed profiles have significant impacts on the calculation of energy consumption, we have refined this function to simulate actual train running based designated running time as accurately as possible based specified running time[2]. When the speed profile for energy consumption estimation is developed, coasting is inserted for the shortest running time and the profile for specified running time is completed.

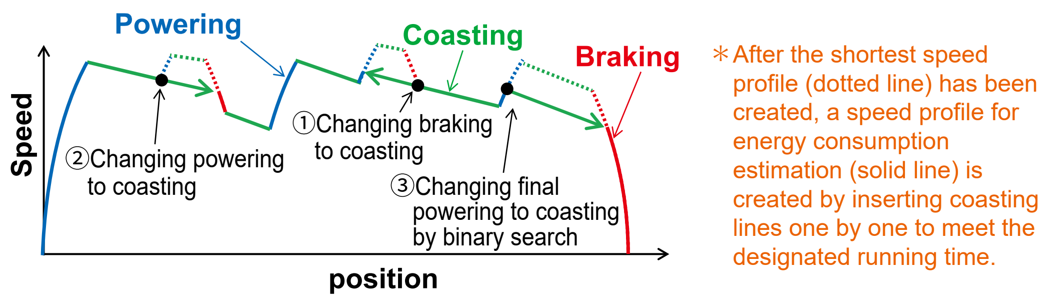
The power to operate trains is divided into traction circuit power to accelerate and decelerate trains and auxiliary circuit power for cabin lighting and air-conditioning. Since the power load for air-conditioning fluctuates significantly depending on the seasons, seasonal adjustment is necessary when calculating it. *Auxiliary power load depending on outdoor temperatures* shows an example of seasonal fluctuation of auxiliary power. As the dots plotted in *Auxiliary power load depending on outdoor temperatures* indicate, more auxiliary circuit power is used for heating in cold seasons and for cooling in hot seasons. To adjust this fluctuation, the simulator sets the fluctuation pattern of auxiliary circuit power as is shown with the orange-colored line.

The Train Operation Power Simulator has been verified through numerous test measurements[3]. Here, an example of predicting daytime energy consumption at a substation is shown. Since the energy consumption at substations also fluctuates due to changing air-conditioning power load, the measurement was continued over total a year and used as data for verification.

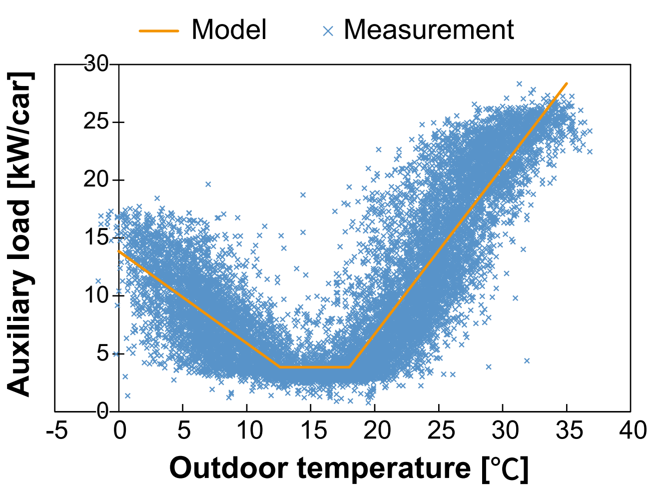
Verified energy consumption depending on outdoor temperatures shows the results. Although measurement results fluctuate due to reasons different from changing outdoor temperatures, the distribution of calculation results is similar to average measured values. Thus, Train Operation Power Simulator can predict the energy consumption of train operations.

Energy-saving effects of energy storage systems

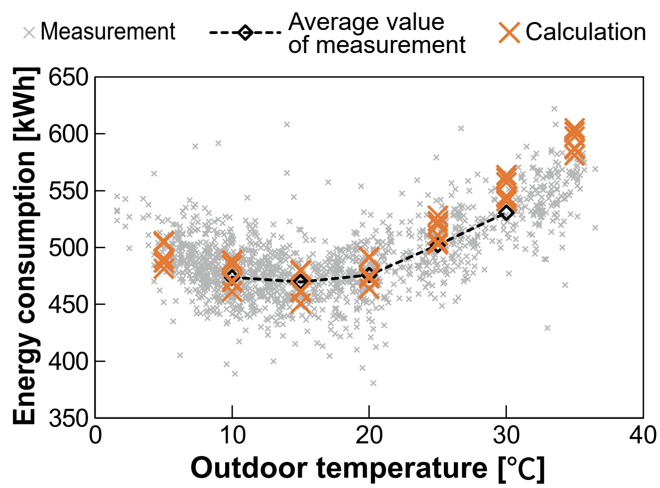
An example of predicting the energy-saving effects of an energy storage system to store regenerated power is described here. It is known that regeneration restriction is likely to occur in spring and fall when the air-conditioning power load is small. Therefore, the energy storage systems controlling regeneration restriction



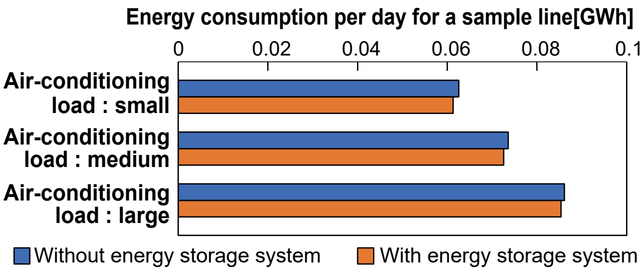
Creating a speed profile for energy consumption estimation



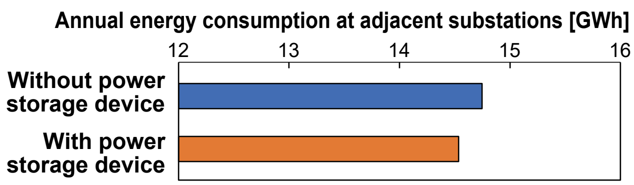
Auxiliary power load depending on outdoor temperatures



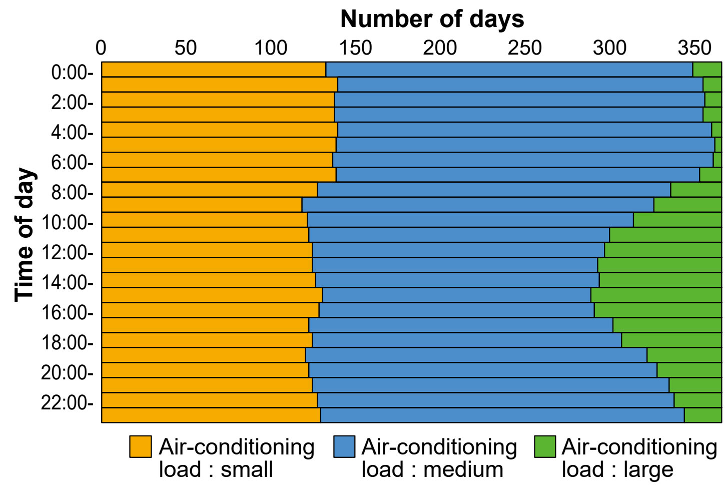
Verified energy consumption depending on outdoor temperatures



Energy consumption by air-conditioning power load



Energy consumption at substations with or without power storage device



Number of days for each air-conditioning load

have larger impacts on energy-saving by preventing regeneration restriction in spring and fall, but smaller impacts in summer and winter. Thus, seasonal fluctuation in air-conditioning power load needs to be considered when the effects of energy storage systems are estimated. RTRI has simulated several patterns of fluctuation according to air-conditioning load and calculated energy consumption for each pattern (*Energy consumption by air-conditioning power load*).

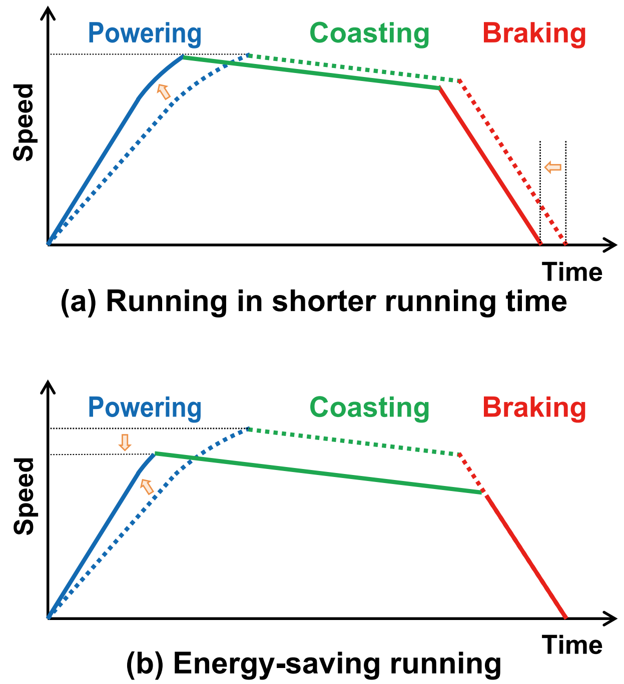
In this example, air-conditioning power loads are divided into three patterns and daily energy consumption for each pattern is calculated. Then the numbers of days in a year for each pattern are calculated based on the outdoor temperature data obtained from the database of the Japan Meteorological Agency (*Number of days for each air-conditioning load*). In the example here, similar air-conditioning load has been identified on an hourly basis using the outdoor temperature data for one year. Then annual energy consumption is predicted by multiplying daily energy consumption in each air-conditioning pattern by the number of days (*Energy consumption at substations with or without power storage device*).

Energy-saving effects of new types of vehicles

The next example shows prediction of energy-saving effects of new types of vehicles equipped with energy-saving motors and inverters. In general, since the weight and tractive effort are different between the new types of vehicles and existing ones, their accelerations are also different. This example shows energy-saving effects and reduced running time by introducing new vehicles with significantly improved acceleration.

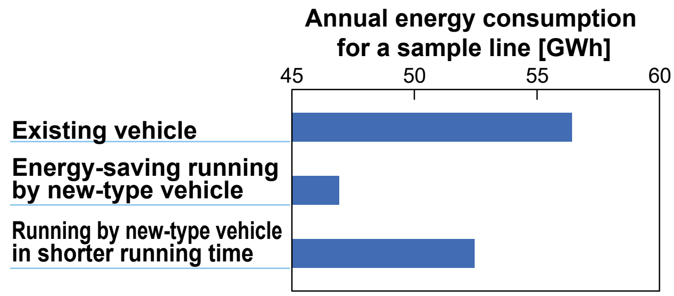
There are two running patterns for the vehicles having high-acceleration performance. One is reducing running time by improved acceleration (*Running pattern for improved acceleration (a)*). The other is increasing coasting time by quickly accelerating and shifting to coasting earlier (*Running pattern for improved acceleration (b)*). In the latter pattern, if the running time is unchanged, coasting can be started at lower speeds, which leads to reduced energy consumption. Therefore, if the acceleration performance of vehicles is changed, it is necessary to estimate the energy consumption under proper running patterns. If energy-saving devices are installed on the new types of vehicles, further energy-saving benefits from vehicle equipment with improved efficiency can be expected. Both energy-saving effects by the changed running patterns and energy-efficient equipment need to be accurately estimated.

The energy-saving effects of new types of vehicles have been estimated under different conditions. We have compared the cases where a new type of vehicle runs in the same running time as an existing vehicle and where it runs for a shorter running time. For the same running time,

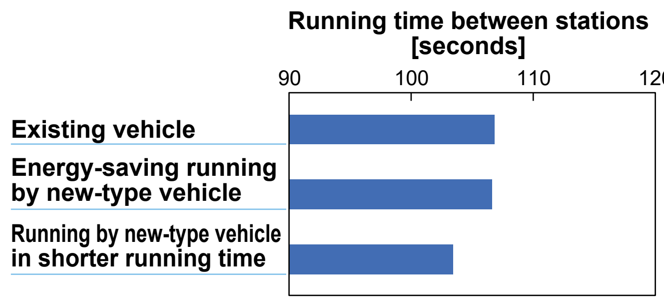


(Solid line: new-type vehicle , broken line: existing vehicle)

Running pattern for improved acceleration



Difference in energy consumption by vehicle type



Difference in running time by vehicle type

the function of the speed-profile for energy consumption estimation sets the running pattern according to the current train timetable. The results are shown in *Difference in energy consumption by vehicle type* and *Difference in running time by vehicle type*. Difference in energy consumption by vehicle type shows total energy consumption, and Difference in running time by vehicle type shows running time for one section between stations. The energy consumption of the new type of vehicle is reduced when the running time is shortened in this example. However, the energy-saving effect is larger if it runs for the same running time. As is indicated by this example, improved acceleration performance contributes to shortening running time as well as to reducing energy consumption.

Conclusion

This article has introduced the method to predict the effects of energy-saving technologies using the Train Operation Power Simulator. We will continue the research into effective ways of introducing these technologies by evaluating their effects with this method.

Part of this research was funded by railway technology development subsidy of Ministry of Land, Infrastructure, Transport and Tourism.

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RTRI's Researcher Given an Award for His Contribution to Railway Technology Standardization

Mr. Kazumasa KUMAZAWA of RTRI received the Year 2021 Award for Contribution to Standardization by the Railway Technology Standardization Survey Committee. The award ceremony took place on March 30 at Plaza F in Tokyo.

Award winner :
Mr. Kazumasa Kumazawa,
Assistant Senior Researcher,
Transport Operation Systems,
Signalling and Operation Systems Technology Division

Award winning achievement :

Participating in a domestic working group to deliberate international standards on railway timetabling since 2016, Mr. Kumazawa has contributed to compilation of the Japanese opinions for international standardization. In particular, he has been a core person in preparing technical details of the international standard draft, ISO WD 24675 (Running time calculation for timetabling - Requirements). He has also served as an international expert of ISO/TC 269/SC 3/WG 3 (Railway timetabling), appointed by the Japanese Industrial Standards Committee, and is expected to further contribute to these activities.

*The Award for Contribution to Standardization is given to persons who contribute to international and domestic standardization activities in the railway field. This award was first made in 2007 by the Railway Technology Standardization Survey Committee (Chairperson: Hiroyuki Osaki, Professor of the University of Tokyo, Secretariat: Ministry of Land, Infrastructure, Transport and Tourism and RTRI). Its purpose is to support the activities of award winners and raise the awareness of the importance of standardization among others working in the industry. In particular, the Award for Contribution to Standardization is given to someone who is expected to continue to contribute to standardization.

Railway Technical Research Institute