Trends in Energy-saving Technology for Multiple Units from the Viewpoint of the Energy Consumption Rates of Railway Companies in Japan

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Ever since the beginning of railways, energy saving has been a key issue for railway companies. An energy consumption rate for the passengers, which is obtained by dividing energy consumption by the number of passenger-kms, is a useful index to demonstrate the effectiveness of saving energy technology. It is well known that the energy performance of passenger railways surpasses that of other modes of transport such as cars, buses and airplanes. The energy consumption rate of Japanese railways is published officially every year. Furthermore, individual railway company energy consumption rates can be calculated by dividing their energy consumption by the number of passenger-km, which both appear in official reports. This paper gives the distribution of railway company energy consumption rates and examines and describes trends in energy saving technology based on this distribution.

Keywords: rolling stock, energy saving, energy consumption rate, passenger-km

1. Introduction

Railway operators have been trying to cut the cost of power used by their rolling stock since steam locomotives appeared and before the term ‘energy saving’ was coined.

The “Centennial History of Japanese National Railways (JNR),” says that tremendous effort was invested in reducing the cost of coal for train operation. It also describes that coal consumption per kilometer of steam engines was reduced by about one quarter between 1920 and 1936. Modernization of power supplies ( electrification and use of diesel) on the JNR after World War II significantly increased power conversion efficiency. During that period, Japanese railways entered the age of electric multiple units. The urgent need to save energy in the wake of the oil crisis in 1973 positively influenced the transition from rheostatic control to chopper control. Today, inverter control is prevalent. The current priority is to reduce CO2 emissions, considered to be the cause of global warming, and this is driving efforts to save even more energy.

In order to facilitate the discussion around energy saving, methods and measures were categorized and reviewed. Figure 1 shows one example of such categorization.

Energy consumption rates are officially published by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) as an index to show energy consumption per mode of transport. In the case of passenger transport, the rate represents the energy used to transport one person for one kilometer, which is a macroscopic value found by dividing the energy consumed by all trains operated in Japan by the number of passenger-kilometers. The railway statistics annual report also gives the number of passenger-kms, electric energy consumption and light oil consumption for train operation per operator, which can be used to calculate energy consumption rate per operator.

This study examined the distribution of results for the 175 surveyed operators and estimated what their energy saving goals could be in the future. With regards to energy consumption rates, i.e. energy efficiency of a means of transport, Sumi et al., produced a detailed report based on the assumption that the number of passengers equaled riding capacity [1]. Moreover, Ohno et al., measured the power consumption and calculated the energy consumption rates for a variety of vehicles, including commuter trains, subways, trams and monorails [2].

2. Overview of energy consumption rates

Energy consumption rates are used as indices and indicate the superior energy consumption performance of railways. Figure 2 shows a graph of the data (passengers) by transport mode in 2011, which was the last fiscal year when the data for owner-driver cars was officially reported. In addition, Figure 3 shows a transition of the energy consumption rate of railways. The energy consumption rate is lower for railways than other means of transport and appears to be gradually improving when seen from a broader perspective.
found that some operators were counting energy used on the 3.1 Distribution and grouping method

operator density, therefore, they were compared (Fig. 4). The latest available annual report railway statistics figures from 2015 were produced to produce the distributions. However, when environmental reports, etc., posted on the websites of railway operators were compared with the annual report figures, it was found that some operators were counting energy used on the ground such as air conditioning, lifts and escalators in stations, etc. in the energy used for train operation. Accordingly, data for companies with high passenger/km volumes was modified taking this into account.

The annual report groups operators into four categories: 16 leading private companies, small and medium-sized companies, public operators and Japan Railway Companies (JRs). Third sector organizations were included in the small and medium-sized company category. This report divides operators into 9 categories to separate electric traction and diesel traction, and distinguish cable cars, monorails and automated people movers from adhesion traction systems using steel wheels and rails, as far as possible:

“JRs and leading private railway companies”; “Subways”; “Small and medium-sized companies (electric traction)”;

“Small and medium-sized companies (diesel traction)”; “Trams”; “Cable cars”; “Monorails”; “Automated people movers”; and “Others”

Here, “Subways” means all public operators except those running trams. The Tokyo Metro Co., Ltd. fell into the leading private railway company category. Static data for electricity and light oil consumption were not as finely categorized as above. Therefore, if a private railway or public traffic operator was involved in more than one category of transport listed above, the energy consumption rate for each category was not calculated individually. However, if one category represented over 95% of the passenger-km data, then it was plotted under that category heading. If the data did not clearly fall more into one category than another, the data for that operator was not plotted.

Based on the graph the following can be said:

- The graph confirmed the logical hypothesis that operators with high transport densities generally would have low energy consumption rates.
- Operators were grouped into 9 categories. Energy consumption rates starting with the lowest first, fell roughly into the following order:
  1. “JRs and leading private railway companies” and “Subways”;
  2. “Monorails” and “Automated people movers”;
  3. “Small and medium-sized companies (diesel traction)” and “Trams”; and
  4. “Cable cars”.

However, as the energy consumption rate varies with the load factor, this order is not necessarily true for all transit systems.

What it does show is a snapshot of the current status of Japanese operators.

- The energy consumption rate distribution for “small and medium-sized companies (electric traction)” was broad. This is thought to be because operators in metropolitan areas were included in the same category as smaller local operators.
- The lowest energy consumption rate among operators was 236 (kJ/passenger-km). The energy consumption rates for the current fiscal year have not been officially reported. However, the rate was about two-thirds of the 369 (kJ/passenger-km) reported in the next most recent report from 2013.
- Energy consumption rates for operators in the “Subways” group were almost equal to the “JRs and leading private railway companies”. This is considered to be because their operating speeds are relatively low, although it was assumed that the energy consumption rates would be higher due to air resistance in tunnel sections.
- Operators of “Trams” were grouped into another category separate from “small and medium-sized companies (electric operation)”. However, comparing operators with comparable transport densities showed no difference in energy consumption rates. In order to understand this, load factors and other situational conditions.
Monorails and automated people movers were considered to have a higher running resistance than steel-wheel and steel-rail systems, therefore it was assumed that their energy consumption rates would rise. However, no such increase was found. In order to understand why, operator data need to be analyzed, as described in the preceding paragraph.

“Small and medium-sized companies (electric traction)” and “small and medium-sized companies (diesel traction)” were found to have different transport densities.

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![Fig. 4 Relationship between transport density and energy consumption rate](image)

### 3.2 Future energy saving goals

Railway operators invest great effort to let more customers ride on longer distances and to adapting the number of cars, which form part of the measures put in place to decrease energy consumption rates.

The remaining section of this paper discusses technical measures applied to reduce energy use by trains, including:

- Application of the latest traction circuit systems equipped with regenerative brakes;
- Applying lightweight, stainless steel or aluminum alloy car bodies;
- Replacement of fluorescent lamps with LEDs;
- Reduction of air resistance on Shinkansen and other high-speed trains;
- Installation of energy storage systems to avoid restricting regenerative braking and regeneration cancelation caused by missed timings between braking trains and powering trains;
- Reducing the chances of restricting regenerative braking by simultaneous inbound and outbound line feeding; and
- Installing regenerative inverters in substation allowing regenerative electric power to be returned to the power grid.

The future of train operating energy saving techniques for the time being depends on two aspects: dissemination and deepening of the above listed techniques.

If a steel car body with a rheostatic control car produced several decades ago were replaced by the latest type of inverter control car with a lightweight body, power consumption could be cut by half, together with the effect of regenerative braking. Although some private railways and subways use almost entirely vehicles equipped with inverters, more recently new inverter technology involving switching elements or diodes using SiC (Silicon Carbide) is being introduced, opening the way to further energy savings compared to previous inverter cars, because of the extended regenerative braking region and loss reduction. Consequently, further improvements, even to the above-mentioned top runners can be expected in the future.

As performance improves it is expected that regenerative braking will be restricted more and more, because the amount of regenerative energy will increase, increasing the importance of measures that can make effective use of regenerative brakes, such as installation of an energy storage system. Lithium ion secondary batteries which are often used as energy storage devices, and are expected to become more popular as they become less expensive and higher performing, reducing prices and enhancing performance. Additionally, development of more excellent energy storage devices is also expected.

If the actual energy consumption data of a train between stations was analyzed, energy consumption would vary up to dozens of percent, even though the amount of time required is the same [3]. One explanation for such variation is difference in driving modes, such as notch selection, timings of notch off and brake application. Therefore, if a suitable driving mode was found to save energy and this was shared among all drivers, significant results could be achieved [3]. Since the appropriate driving mode will vary from day to day according to the many elements that intervene, such as trains being on time or delayed, operational time margins and restrictions on braking due to weather conditions, such as rain and snow, it may be difficult for humans to decide which measure can produce the optimum effect. However, if autonomous driving becomes a reality, software could have effective energy-saving algorithms built in.

Engine/battery hybrid multiple units and overhead contact line/battery hybrid multiple units are used in practice as alternatives to diesel multiple units in JR East and JR Kyushu. With these vehicles, energy consumption is reduced by using regenerative brakes etc.. Again, price reduction and performance enhancement of batteries will be decisive in the mainstreaming of such vehicles, in the same way as the energy storage system above.

Recent years have seen the installation of a growing number of elevators and escalators to improve station accessibility, which, together with development of air conditioning systems, tends to raise energy use on the ground - however this subject falls outside the scope of the present paper. There are some cases where subways consume more energy on the ground than train operation energy. As station equipment needs to be further developed in the future, it is also important to consider how to suppress any increase in energy consumption due to new facilities being installed.

4. Conclusion

As stated at the beginning of this report, energy saving has always been a priority issue, reflecting evolving needs and expectations over time. Today the energy saving properties of railways are once again being recognized globally, and many projects including high-speed rail are under way. Efforts will continue to enhance the attractiveness of the railways as sustainable transport solution for the future.

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