Recently Studies and Developments of Energy Saving Technologies in the Field of Railway Vehicles

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In the 1990s, energy saving technologies in the field of railway vehicles had not been wrestled with actively because of a cost-benefit point of view. In the 2000s, they had been interested in decreasing greenhouse gas as a countermeasure against global warming. In the year of 2006, the revised Rationalization in Energy Use Law obliged major railway companies which owned more than three hundred vehicles to report on the plans and actual results of their measures for the reduction of energy consumption, with the result that further countermeasures are sought after. This report introduces the recent studies and developments of energy saving technologies in the field of railway vehicles.

Keywords: energy saving, high efficiency induction motor, search method for energy saving operation

1. Introduction

Railway vehicles have low running resistance, making railway much more energy saving than automobiles and aircraft. In the 1990s, while a modal shift to railway from other means of transport was actively encouraged, efforts to make railway vehicles more energy saving especially from the viewpoint of cost efficiency faced a hurdle. That is, it was difficult to cover energy saving costs with just the reduction in electricity bills and fuel consumption. To help overcome the hurdle, aluminum material was introduced on Shinkansen bodies to make them lighter and, along with the advancement in power conversion technology, highly efficient inverter/induction motors were introduced. Other than these, there were no earnest efforts to develop energy saving technologies. In the 2000s, amid increasing attention to the need to cut emissions of greenhouse gases to stem global warming, in 2006 the Revised Act on the Rational Use of Energy came into effect, obligating railway operators with a minimum fleet of 300 railway vehicles to take energy saving measures. This, along with other requirements, made it important to take further energy saving measures. As part of the effort, old engines on power cars used in non-electrified sections were replaced with new engines and non-regenerative vehicles in electrified sections were replaced with vehicles equipped with the latest VVVF inverter/induction motor technology. Even with these measures, however, some of the railway operators are nearing the limit of energy saving. New energy saving technologies are therefore keenly sought. With that background in mind, this paper presents the latest research and development efforts on energy saving railway vehicles.

2. Energy consumption by railway vehicles

Table 1 shows the energy consumed by railway vehicles as they run. With the energy for driving which accounts for the bulk of the total energy consumed by railway vehicles, assumption was made on the proportions of the losses and on the energy saving effect of reducing the train mass and the first- and second-order terms of running resistance. Operation curves calculated with RTRI’s Hybrid-Speedy [1] under the running conditions in Table 2 are shown in Fig. 1. The effect of reducing the factors in comparison with no reduction (100) is shown in Fig. 2. It was found from the calculation that losses due to constant terms of running resistance and starting resistance are both extremely small and that losses due to first-order terms of running resistance and the main circuit are both quite large, each accounting for roughly one third of the total loss. It also became clear that reducing the train mass by 20 % led to a roughly 20 % reduction in energy consumption. The results of the calculation in which a train was run under the conditions of Table 2 can only be used as a reference. Results can change

Table 1 Energy consumed by railway vehicles

| Energy for driving | Energy consumption by railway vehicles |
|--------------------|---------------------------------------|
| Loss due to constant terms of running resistance (Mechanical loss) |
| Loss due to first-order terms of running resistance (Mechanical loss) |
| Loss due to second-order terms of running resistance (Air resistance loss) |
| Loss due to starting resistance |
| Loss due to braking |
| Loss due to main circuit |
| Loss due to gears |
| Air conditioning |
| Ventilation |
| Heating |
| Lighting |
| Air compressors |
| Control power |

Table 2 Running conditions used for calculating proportions of losses

| Train set | 3M4T (7-car train) |
|-----------|--------------------|
| Main circuit type | Inverter + Induction motor (Regenerative) |
| Mass | 250,000 kg |
| Running distance | 3 km |
| Running time | 160 seconds |
| Vehicle application | Commuter / Suburban |
than red brass, cut approximately in half the loss caused by the conductor. For the iron core, the conventional 50A800 is replaced with the 35A300. These codes are based on “JIS C 2552: Cold-rolled non-oriented electrical steel strip and sheet delivered in the fully-processed state.” The first two digits indicate thickness while the last three digits indicate the magnitude of iron loss. With the change in material, iron loss is expected to be down to three eighths of the previous level. For the stator winding, the conventional glass insulated wire is replaced with Kapton insulated wire to increase the space factor of the conductive winding.

The second method optimizes the number of coil turns of the stator winding. The number of turns of the conventional stator winding is 72, which is intended to reduce inverter capacity. Reducing the number to 54 improve the efficiency of the traction motor and also regeneration performance in the high speed range.

The third method relates to a new design for the rotor. Secondary harmonic wave copper loss occurs in the area above the rotor-bar conductor within the rotor slot. Therefore, the new design positions the rotor-bar conductor away from that area (Fig. 3).

In the fourth method, as a result of reduction in heat value achieved through the methods 1 to 3 over the conventional motor, mechanical loss can be reduced by making the cooling fan smaller and closing the air vent for the rotor.

![Fig. 1](image1.png)  
**Fig. 1** Calculated operation curves showing energy consumption of railway vehicles while running

![Fig. 2](image2.png)  
**Fig. 2** Proportions of losses and the effect of reducing the factors

depending on train applications and running distances.

3. Examples of research and development on energy saving

This chapter discusses examples of research and development by RTRI on energy saving that can be used for practical applications, including the high efficiency induction motor and the search method for energy saving train operation.

3.1 High efficiency induction motor [2]

As discussed in Chapter 2 and shown in Fig. 2, the main circuit generates a substantial loss in energy. The loss is generated at the reactor, inverter and traction motor. The traction motor has an efficiency rate of 91 to 93 % while the reactor and inverter have much higher efficiency rates, meaning that much of the loss in the main circuit is generated at the traction motor. Improving the efficiency rate of the main induction motor, therefore, contribute greatly to the reduction in energy consumption.

3.1.1 Loss reduction methods

The first method uses low loss materials. The rotor-bar conductor is traditionally made of red brass. Replacing red brass for silver-copper alloy, which has lower resistance than red brass, cut approximately in half the loss caused by the conductor. For the iron core, the conventional glass insulated wire is replaced with Kapton insulated wire to increase the space factor of the conductive winding.

The second method optimizes the number of coil turns of the stator winding. The number of turns of the conventional stator winding is 72, which is intended to reduce inverter capacity. Reducing the number to 54 improve the efficiency of the traction motor and also regeneration performance in the high speed range.

The third method relates to a new design for the rotor. Secondary harmonic wave copper loss occurs in the area above the rotor-bar conductor within the rotor slot. Therefore, the new design positions the rotor-bar conductor away from that area (Fig. 3).

In the fourth method, as a result of reduction in heat value achieved through the methods 1 to 3 over the conventional motor, mechanical loss can be reduced by making the cooling fan smaller and closing the air vent for the rotor.

3.1.2 Reduction in electricity consumption

To evaluate how much less energy the newly developed high-efficiency induction motor would consume, running simulation was conducted to measure the electricity consumed. Figure 4 shows reduction rates of electricity consumption in relation to station-to-station distances.

As shown in Fig. 4, the new high efficiency induction motor consumed about 10 % less electricity. When higher regeneration performance is considered, the reduction rate should improve up to 24 %. While the new motor has an efficiency of about 96 %, which is just 3 % higher than the 93 % efficiency of the conventional motor, the loss in the entire main circuit is down by about a third, which corresponds to about a third (10 %) of the main circuit loss in Fig. 2. When higher regeneration performance is considered, it corresponds with the part of braking loss (15 %) in Fig. 2.
3.2 Search method for energy saving train operation [3]

The amount of energy consumed by railway vehicles is known to change depending on how the train is operated. Methods currently employed to find ways to reduce energy consumption include running test and simulation. These methods, however, require numerous settings of conditions and related time and labor. On the other hand, the search method features an algorithm that, with a single input of running conditions and time schedules, searches for train operation with least consumption of energy, calculating energy consumption and producing energy saving operation curves that approximate actual operation.

3.2.1 Search algorithm for energy saving train operation

The search algorithm first creates reference operation curves and defines the time schedule as $T_0$, then searches for operation curves that require least electricity consumption during or less than the preset time schedule $T_{max} (\geq T_0)$ by looking for combinations of train control maneuvers that help save energy, such as changing the brake notch and coasting wherever appropriate. Coasting is programmed wherever the largest amount of electricity is saved per unit time, which helps make the algorithm greedy.

3.2.2 Energy saving achieved by the search method in comparison with conventional methods

For comparison, examples of operation curves created by the search method for energy saving train operation and those based on two of the widely used energy saving train operation methods (no repowering and operation within the maximum speed limit) are shown in Fig. 5, and calculated energy consumptions based on these operation curves are shown in Fig. 6. All of these operation curves are for a running distance of 1,300 m and a running time of 111 seconds.

Among the three methods, train operation with no repowering consumed the least electricity in powering. However, the no repowering method achieved the least regenerated electricity as the initial braking speeds were rather low, resulting in being the second best energy saving method after the search method. With the search method, notch-off timing is considered to be ideal for both powering and repowering, helping to make the method the most energy saving among the three options.

3.3 Other examples of RTRI research and development

3.3.1 Vehicle weight reduction technology

As discussed in Chapter 2, making railway vehicles lighter significantly improve their energy saving performance. With that in mind, review has been started on the possibility of replacing some of the metal body structures and parts for FRP material [4].

Fire resistant magnesium alloy samples were produced for possible application as body structure material for weight reduction, and the samples were analyzed to identify their structural and mechanical properties and workability. Efforts are also being made to secure enough stiffness by looking into the possibility to produce hollow extruded shape material and appropriate welding and joining methods [5].
3.3.2 Reducing air resistance of conventional line vehicles by reshaping [6]

Wind tunnel tests and other experiments suggested the possibility that the coefficient of air resistance (second-order terms of air resistance) would be reduced by up to 22 % on conventional line eight-car trains by reshaping the roof-top and underfloor equipment. This possible benefit, according to the publication "6" listed in "References," would translate into a 5.4 % reduction in energy consumption. On the other hand, in Fig. 2, reducing the second-order terms of running resistance by 20 % would lead to a reduction in energy consumption of just 3 %. The difference can be attributable to the fact that the maximum speed in operations of Fig. 2 is about 90 km/h while that of the publication "6" is 130 km/h, with the probable consequence that the proportion of the energy consumed by the second-order terms of running resistance in the overall energy consumption of the publication "6" is higher than that of Fig.2. The reshaping technology has been refined almost to the level of practical application.

3.3.3 Energy saving technology by mounting batteries on vehicles [7]

Modern electric railcars produce regenerated electricity from braking. When there are no electric railcars nearby, regeneration is either cancelled or limited. Braking force is always available for safety as the mechanical brakes activate automatically. This, however, increases energy consumption. By mounting batteries on vehicles, the regeneration limitation and the cancellation are prevented. Vehicles equipped with batteries will be improved regeneration performance in high speed, also have less braking loss, and offer regenerative braking and thus energy saving benefits in non-electrified sections. This technology has also been refined nearly to the level of practical application. It is currently used in commercial operation of the EV-E301 [8] series at JR East. And running test was conducted on the technology as well using modified 817 series AC electric railcars at JR Kyushu [9].

3.3.4 Development of fuel cell vehicles [10]

As a replacement for diesel cars in non-electrified sections, a fuel cell-battery hybrid vehicle is being developed to achieve substantial reduction in energy consumption by tapping the high efficiency of fuel cells and utilizing regenerative braking in non-electrified sections. As they only emit unused air and vapor, fuel cell vehicles are drawing keen attention as an extremely clean, next-generation solution for non-electrified sections. Currently, a test vehicle equipped with a 100 kW fuel cell system, batteries and other components is undergoing running test at RTRI to assess long-term degradation characteristics. The development program has been partly subsidized by Ministry of Land, Infrastructure, Transport and Tourism.

3.3.5 Development of a magnetic heat pump system [11]

Currently, vapor compression refrigeration systems based on alternative CFCs are mainly used for cooling vehicles. However, alternative CFCs are designated as gases whose emission should be limited. As an alternative, magnetic refrigeration technology with high refrigeration efficiency is drawing attention. It is also called magnetic heat pump technology as it is also used for heating at room temperature. In a research and development program on magnetic heat pump technology commissioned by the New Energy and Industrial Technology Development Organization and carried out jointly with Chubu Electric Power, Sanden, Santoku, Tokyo Institute of Technology, Kobe University and Kyushu University, a magnetic heat pump system with the maximum refrigeration capacity of 1.4 kW was achieved.

3.3.6 Applying high efficiency waste heat recovery cycle to railway vehicles [12]

Recovering waste heat from exhaust gas and engine coolant of diesel cars helps fuel efficiency and energy saving. A high efficiency recovery system is being developed with a focus on the trilateral cycle. Currently, efforts are being made to maintain efficiency through visualization of boiling conditions in the cylinders and boiling induction. This research and development effort has been commissioned by the Japan Science and Technology Agency (JST).

4. Conclusion

This paper presents eight technological undertakings ranging from those that will be practically applied to those that are still in the basic stage. For those practical technologies, much still needs to be figured out how these will be effectively presented to railway operators so that they feel like adopting these technologies. For those potential candidates still at the basic stage, further efforts must be made to expeditiously develop them into practical and useful applications for railway operators.

It was mentioned in Chapter 2 that losses due to first-order terms of running resistance are quite large. It was also mentioned that braking loss in high speed range is rather large. These energy losses should be considered as offering great opportunities to improve energy efficiency. Continuous efforts should therefore be made to refine research and development methods and improve energy efficiency for railway vehicles including on but not limited to those areas.

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