Challenge A: A more and more energy efficient railway

Study on the energy saving running technology and its CO₂ reduction effect of railway vehicle

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Abstract

It is inevitable that companies all over the world will embrace green growth and adopt sustainable technology, because current environmental regulation and standards, such as the Kyoto protocol, IPP, EU P, WEEE, ISO and 14064, mandate such changes. Under these strict new environmental requirements, railway vehicles must reduce energy consumption, lower emissions, and increase recycling rates. A railway vehicle consumes energy over its entire life cycle, from production to disposal. According to an analysis conducted by Siemens, the majority of this energy is consumed during the vehicle’s operational phase. In order to lower energy consumption during this stage, railway manufacturers and operators are trying to develop new technologies, such as light weight materials for reducing the total weight of rolling stock, energy storage systems that make it possible to use regenerative electric energy, eco driving systems that reduce stops, and optimize HVAC systems. In this paper, the optimization and reduction of internal energy consumption through the use of regenerative energy and on-situ eco driving technology was researched. This technology can be achieved by applying small capacity, light weight energy storage systems to the underside of rolling stock. This energy storage system, which is different from super capacity systems, is used to power internal electricity such as lightening and HVAC systems, and not for the vehicle’s driving electricity. With this technology, we can achieve two goals; decreasing vehicle weight, and making full use of the regenerative energy, which is otherwise burned off by resistors. Regenerative energy is about 25% of the vehicle’s total running energy. If we use more than 20% of the regenerative energy, it will not only save electricity and reduce global warming, it will also improve the efficiency of railway operation. This goal can be achieved by simplifying eco driving simulation factors. Instead of using the regenerative energy of a breaking vehicle to power another vehicle’s launch, it is more efficient to use the energy to power the breaking vehicle’s internal electrical devices.

1. Introduction

Statistics from various countries show that the transportation sector is responsible for about 20-30% of the world’s greenhouse gas emissions. Analysis shows that road transportation, such as automobiles, accounts for the majority of the pollution, whereas railway transportation accounts for only 2-4%. This is evidence that railway travel is currently the most eco-friendly mode of transportation [1]. However, the recent imposition of stricter environmental standards has made it necessary not only to reduce greenhouse gas emissions produced during a vehicle’s operational phase, but also to improve environmental performance throughout a vehicle’s entire life cycle. In response to such regulations, the automobile industry is working to achieve zero emissions by exploring such options as alternative energy, hybridization, and lightweight materials [2]. Unless the railway industry mounts a similar effort to improve environmental performance, railway transportation will be responsible for much more than the 2-4% of greenhouse gas emission that it currently produces. Many European countries are taking steps to reform their transportation systems, starting with railway transportation. In addition, the UIC is in the middle of an ongoing effort to improve the environmental performance of railways by applying the life cycle-based environmental requirements adopted by other industries [3]. Europe, in particular, applied a life cycle assessment (LCA) to the railway industry early on. It has since been working to quantify the energy consumption of railway vehicle materials and main operational components by function, thus developing technologies for improvement [4]. Reliable LCA can be achieved by building a life cycle inventory (LCI) database for the various materials used in a particular product. In Europe, there is already a solid foundation for applying materials based on environmental factors, such as potential energy consumption and recyclability during the design phase, in the form of an integrated database of materials and material-specific environmental performance by industry sector. The primary objective of railway environmental policies and R&D technology is to improve energy efficiency at the operational phase, one anticipated effect being the reduction of greenhouse gas emissions. Energy efficiency at the operational phase can be improved.
by applying environmentally-friendly design techniques that take a comprehensive account of railway materials, manufacturing, and operation. One good example is the work of the Center of Competence for Design for Environment (CoCDfE) at Bombardier. The CoCDfE team has been devising and distributing environmentally-friendly railway vehicle design techniques and checklists, and building a company-wide system for incorporating such elements into the manufacture of railway vehicles [5]. On this foundation, it has recently begun work on the ECO4 (Ecology, Energy, Efficiency, Economy) project, which is expected to improve the environmental performance of railway vehicles by over 50% [6].

2. Current technology review

2.1 Life cycle assessment and eco-design of railway vehicle

It is imperative that the green house gas (GHG) emissions that are produced during the entire life cycle of a product be reduced. The current global warming problem is the result of mass production techniques that only focusing on technology development. Ecodesign is one solution that will help us meet new environmental standards, such as sustainable development and low-carbon, green growth. Ecodesign is a systematic approach that seeks out ways to minimize the environmental impact of a product throughout its entire life cycle[7]. These stages include the extraction of the raw materials, manufacturing, marketing and distribution, the operational phase, and finally, the disposal of the product. Products produced using ecodesign include hardware and software. Ecodesign was a creation of end-of-the-pipe technology, a popular policy for environmental protection. Prevention became the primary goal in the attempt to reduce waste and toxic substances in the production stage, a process known as clean production. Next, minimizing the environmental impact of a product was promoted. This applied to the entire life cycle of a product, from raw material extraction to the ultimate disposal of the product, which is called clean product. The current goal is to optimize the entire socio-economic system of the product and its uses in an effort to meet the criteria of sustainable development for the future [8]. The environmental assessment involves the identification, quantification, evaluation, and prioritization of environmental aspects in relation to a product system. For this, effective environmental assessment tools are required. Recently, life cycle assessment (LCA) and matrix methods have widely been used to evaluate the environmental performance of a product system [9]. However, a detailed full LCA can be difficult to apply at the design stage because it is tedious, expensive, and time-consuming. Therefore, there is a need for cheaper, faster, less labor intensive methods that are able to provide adequate results in more detailed and costly exercises [10]. The low-carbon product design system allows for quick calculations of a product’s GHG emissions. Thus, a designer can quickly and easily evaluate alternative parts for use in the design of a low-carbon product. Case study results show that a low-carbon product design can be simply and easily applied in the evaluation of alternative design solutions, thus making low-carbon product design possible during the embodiment design stage [11].

Struckl et al. [12] studied the aspect of metro trains, and discusses solutions for reducing their impact on the environment. After identifying the critical parts of the metro train, they recommended ways to improve the vehicle’s environmental safety.

![Fig.1A railway vehicle's potential contribution to global warming throughout its entire life cycle](image)

Fig. 1 shows that the use and maintenance stage of a vehicle’s life cycle is responsible for the greatest amount of global warming, which accounts for about 75% of the total emissions produced. The materials used to manufacture the vehicle come in second, at 40%. From this result, it is clear that operation energy should be decreased in order to improve the environmental performance of the railway vehicle.
2.2 Regenerative energy

In order to reduce the greenhouse gas emissions produced during the use and maintenance stage of a railway vehicle, regenerative energy, which has been largely ignored until now, should be considered. A regenerative brake is an energy recovery mechanism which slows a vehicle by converting its kinetic energy into another form, which can either be used immediately, or stored until needed. This contrasts with conventional braking systems, where the excess kinetic energy is converted to heat by friction in the brake linings, and therefore wasted. The most common form of regenerative brakes involves using an electric motor as an electric generator. In electric railways, the generated electricity is fed back into the supply system, whereas in battery electric and hybrid electric vehicles, the energy is stored in a battery or bank of capacitors for later use.

The results of the Siemens study in fig. 2 [12] show that the amount of regeneration energy is almost 30% during operation. A fact in fig. 2 that is of particular interest is that the amount of energy consumed in the heating of the railway vehicle is almost equal to that of energy recovery.

![Energy balance for the electrical equipment of in metro trains](image)

After identifying the critical parts of the metro train, environmentally related improvements were recommended. The relative saving potentials are based on international studies on energy efficiency for railway vehicles [12].

2.3 Current applications of regenerative energy in railway vehicles

2.3.1 Energy storage technologies for railway vehicles

The energy storage system, a method that enables the use of regenerative energy in railway vehicles, is currently receiving a lot of attention. Several energy storage systems are being considered for use in the railway industry, such as super capacitors, flying wheels, and Li-ion batteries. Because each of these storage systems has pros and cons, it has been difficult to determine which is best suited to railway vehicles. Table 1 shows a brief comparison of a flying wheel and a super capacitor storage system.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Flying wheel (Piller company)</th>
<th>Super capacitor (TGT company)</th>
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<tbody>
<tr>
<td>Capacity for energy charging and discharging</td>
<td>5.0kWh (= 17.8MWs)</td>
<td>1.44kWh (= 5.184MWs)</td>
</tr>
<tr>
<td>Electricity of energy charging and discharging</td>
<td>1000kW</td>
<td>200kW</td>
</tr>
</tbody>
</table>

Mir et al. [13] investigated the design and validation process of a supercapacitor storage based light rail vehicle (tramway). The main design aspects of the storage system are: storage system rating, supercapacitor bank modeling, power electronic converter design and system control, and management algorithms. Based on this design procedure, two 200 kW bidirectional multichannel buck-boost converter modules have been designed and connected to their respective supercapacitor banks. Compared to a conventional light rail vehicle, the designed system has improved efficiency and the ability to circulate in autonomous mode without catenaries. Besides a series of simulations validating different system operation modes, experimental results obtained from a full-scale tramway are also presented. Li-ion batteries are electrochemical energy storage devices that are used in a wide variety of applications. Compared to other storage devices, batteries have very high energy densities, but they have low power density and therefore high charging times. Some modern high
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performance batteries do however reach power densities that could be used for braking energy storage in automotive, and to a smaller extent, railway applications.

2.3.2 PRIMOVE
BOMBARDIER’s PRIMOVE system with MITRAC energy storage allows catenary-free operation of trams over distances of varying lengths, and in all surroundings, as well as on underground lines. The system’s most notable feature is its contactless inductive power transfer with electric supply components that are hidden beneath the track. The MITRAC energy saver works by charging up storage devices with the electrical energy that is released when braking. Each unit weighs about 450 kg. Fig. 3 shows BOMBARDIER’s PRIMOVE and MITRAC system.

2.3.2 Wireless Tram
A wireless hybrid tram system that uses a Li-ion battery is also under development in Korea. The system is important, as it is the first step to shift from a bus system to a tram system for urban public transportation in Korea. Korea had a traditional tram system in the past, but problems such as a complicated electric line led to its demise. Because of increasing concerns about global warming, the tram is once again gaining popularity. One problem with the new concept is that the energy storage system uses a Li-ion battery made by LG Chemical to propel the tram, which makes the storage unit very heavy. Fig. 4 shows the conceptual Korea Tram system.

3. The Eco-operation concept and its benefits
3.1 Energy consumption and weight parameters of railway vehicles
The multiple regression method is used to analyze the relationship between the energy consumption parameters of railway vehicles during the operational stage, which accounts for 70~80% of the energy consumed during the vehicle’s life cycle. The amount of energy consumed by a railway vehicle depends on internal and external factors. In order to evaluate the energy consumption of a railway vehicle during the running stage, data from operating railway vehicles (Seoul Metro and Seoul Metropolitan Rapid Transit Corp.) for the past three years (2006~2008) were gathered for the multiple regression analysis (refer to Table 2). The annual power consumption collected for each operating body reflects various factors that affect the running electricity. Using the multiple regression analysis, the multiple regression equation was determined as seen in eq. 1.

<table>
<thead>
<tr>
<th>Operation company</th>
<th>Line</th>
<th>Vehicle weight (tons)</th>
<th>No. of Passenger (1000person)</th>
<th>Running distance (km)</th>
<th>No. of Stations (ea)</th>
<th>Electricity (real) (MWh)</th>
<th>Electricity (estimation) (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daegu</td>
<td>#1</td>
<td>6,786</td>
<td>61,488</td>
<td>2,918,412</td>
<td>30</td>
<td>36,001</td>
<td>32,168</td>
</tr>
<tr>
<td>SM</td>
<td>#1</td>
<td>6,009</td>
<td>167,287</td>
<td>20,504,140</td>
<td>10</td>
<td>54,512</td>
<td>46,371</td>
</tr>
</tbody>
</table>
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</thead>
<tbody>
<tr>
<td>#2</td>
<td>30,023</td>
<td>719,439</td>
<td>91,945,303</td>
<td>50</td>
</tr>
<tr>
<td>#3</td>
<td>18,865</td>
<td>257,198</td>
<td>52,790,887</td>
<td>31</td>
</tr>
<tr>
<td>#4</td>
<td>16,788</td>
<td>298,894</td>
<td>53,328,581</td>
<td>26</td>
</tr>
<tr>
<td>#5</td>
<td>19,973</td>
<td>597,357</td>
<td>18,591,288</td>
<td>51</td>
</tr>
<tr>
<td>#6</td>
<td>11,152</td>
<td>213,896</td>
<td>6,878,704</td>
<td>38</td>
</tr>
<tr>
<td>#7</td>
<td>16,740</td>
<td>110,519</td>
<td>3,540,108</td>
<td>42</td>
</tr>
<tr>
<td>#8</td>
<td>4,330</td>
<td>216,343</td>
<td>6,285,506</td>
<td>17</td>
</tr>
</tbody>
</table>

| Coefficient | 4.7292 | 0.0104 | 0.0011 | 163.4362 | -8796.6975 |

Multiple regression equation: $Y = 4.73X_1 + 0.01X_2 + 0.001X_3 + 163.44X_4 - 8796.70 \tag{1}$

Where $X_1$ denotes the weight of the empty vehicle, $X_2$ denotes the number of passenger, $X_3$ is running distance, and $X_4$ is the number of station on the line. From eq. 1, we can determine that the relationship between weight and energy consumption cannot be ignored, nor can the number of stations. It is very important to introduce light weight technology in railway vehicles in order to reduce energy consumption during operation. Consequently, the energy storage system for reusing regenerative energy must be light-weight so that it does not affect energy consumption.

3.2 Eco-operation concept

Research on the reduction of vehicle operation energy can be classified into two categories. The first category includes software related to the eco-driving control, simulation during operation, and design of railway vehicles, and the second category includes hardware related to the railway vehicles. Hardware technologies are composed of lighter vehicle manufacturing and storage systems. It is possible to use lighter materials such as aluminum car bodies and composite bogie frames in the manufacturing of vehicles. Storage systems are composed of various technologies. Lithium-ion batteries, flying wheels, and super-capacitors are typical energy storing devices in the railway industry. Up to now, Most of the stored electricity has been reused to power accelerating vehicles. In order to reuse the stored regenerative energy, it is necessary to synchronize the accelerating vehicles that need power with the breaking vehicles that generate the regenerative energy. At this point, that synchronization is a very crucial technology. Synchronization cannot be achieved through eco-driving. The goal of eco-driving is to optimize each vehicle’s energy consumption, which includes the production of regenerative energy. The ideal operation pattern of eco-driving is shown in Fig. 1.

![Fig.3 Operation pattern of eco-driving](image)

In order to synchronize vehicles, eco-control should be included to match the energy point. Eco-control is necessary to maximize the rate of regenerative energy that is used. But the in-situ eco-control of vehicles running at peak times is very difficult because of unforeseen events such as delays and accidents. Because these events make it impossible to follow the planned schedule, real time control technology that will automatically create a new schedule when these events occur needs to be developed. Another important device that should be considered is the storage device. In this study, a Lithium-ion battery was considered to provide the electricity of internal systems, such as HVAC, lighting, and door operation. The storage device does not need to be large capacity or heavy weight, because it would not be used to propel railway vehicles. The key is to generate as much regenerative energy as possible and reuse all of the energy without investing much money. The role of the control post is to monitor the amount of energy in the storage device of each vehicle, optimizing the running schedule in real time, and sending the information to the driver of each vehicle. The graphical concept is shown in fig. 2.

Another benefit of installing the storage system in railway vehicles and using the stored electricity for internal devices is that vehicles do not need to be synchronized because the regenerative energy is consumed by the vehicle that created it. This means that there is no need to consider another vehicle.
3.3 Energy saving effect of eco-operation in urban railway vehicles

The key to using Li-ion batteries as an energy storage device in railway vehicles is to store the electricity for short periods of time. This is because it only takes about 4~5 seconds to generate regenerative energy.

In order to determine the effects of an eco-operation system, certain parameters were set for use in a simulation. These parameters are described below:
- Number of railway vehicles in operation on the same line: 3
- Energy storage device and capacity
  - On board devices: 4
  - Substation devices: 10
- Energy requirement for each running pattern
  - Acceleration: 10
  - Even velocity: 4
  - Drifting: 0
  - Braking: -4

Considering these factors, operation patterns were made and energy consumption was predicted and compared. The results are shown in table 1. The operation patterns of each vehicle, for a total of 3 vehicles, are shown in fig. 3.

![Fig. 4 Eco-operation concepts](image)

**Fig. 4 Eco-operation concepts**

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![Fig. 3 Eco-operation concepts](image)

**Fig. 3 Eco-operation concepts**

In fig. 3, general pattern (a) shows the running pattern of a railway vehicle under normal conditions,
not considering the synchronization of vehicles related to the transfer of regenerative energy. Regenerative considering pattern (b) shows the running pattern in eco-driving control, considering the synchronization of regenerative energy production and consumption at the point where vehicles start and stop. Under the operation patterns of railway vehicles in fig. 3, the consumption rate of regenerative energy is compared and the results are shown in table 1. Table 1 shows that the rate of regenerative energy consumption with vehicle synchronization is higher than that of normal operation. The results of the simulation show that there will be a 37% energy savings if regenerative energy is used on the railway.

### Table 2. Simulation results of energy saving effect

<table>
<thead>
<tr>
<th>Classification</th>
<th>General operation</th>
<th>Regenerative Energy considering operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy usage</td>
<td>%</td>
</tr>
<tr>
<td>Current state</td>
<td>9290</td>
<td>100</td>
</tr>
<tr>
<td>On-board storage</td>
<td>8250</td>
<td>89</td>
</tr>
<tr>
<td>Substation storage</td>
<td>7670</td>
<td>83</td>
</tr>
<tr>
<td>On-board &amp; substation</td>
<td>7670</td>
<td>83</td>
</tr>
</tbody>
</table>

### 4. Conclusion

The key point of this study is that regenerative energy should be reused. It is an inexpensive means of reducing energy consumption that does not increase the weight of the railway vehicle. From the study, it was determined that the reuse of regenerative energy could reduce energy consumption by about 37%. The combined annual electricity consumption of the Seoul railway, Seoul Metro, and Seoul Metropolitan Rapid Transit is about 875,000 MWh. As of now, regenerative energy is not reused for several reasons, including the instability of high voltage, but it is instead burned off through resistors. If eco-operation is adopted, its energy storage systems and reuse of regenerative energy could amount to an energy savings of about 343,171 MWh per year. CO₂ emissions could be reduced by up to 145,500 tons, and the electricity saving could amount to $20 million per year. Because this study only considered the effect of employing eco-driving technology in the Seoul region, more benefits can be expected if it is applied on a larger scale. In order to apply the eco-operation technology suggested in this study to current railway operation systems, other devices must be considered. This can be achieved through the cooperation of several technologies, such as operation scheduling, signaling and controlling, and fast battery charging technology.

### Reference


