Energy-saving train scheduling diagram for automatically operated electric railway

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**Abstract**

Interest in energy-saving railway scheduling and operations is growing because of environmental concerns. Saving energy on both the hardware and software sides is an ever-increasing interest and challenge. Railway scheduling is closely related to the energy consumption of rolling stock. Energy consumption decreases when running time is increased because running curves can include considerable coasting time. However, the running time between two adjacent stations is determined for scheduling, and this running time is adhered to very strictly in Japan. Power-limiting brakes, which use regenerative braking without mechanical braking, are very useful in energy-saving operations. However, power-limiting brakes have some drawbacks, such as slow deceleration and the difficulty of notch operation. How to use power-limiting brakes effectively on schedule remains a research problem.

We propose a method for developing an energy-saving schedule based on automatic train operation (ATO), which offers exceptional control notch performance and is easier to apply to an optimised schedule than manual train operation. In the proposed method, running time distribution is optimised based on energy savings between stations by keeping the total running time constant. Only the running time is optimised, so that additional time-tabling strategies for energy-saving can be applied, such as reducing dwell and turnaround times and increasing running time margins. Practical considerations are included, such as determination of running times as integer values. The results of this study show that energy-saving efficiency is increased when the running time distribution between stations is optimised.

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1. Introduction

1.1. Railways as a key to solving environment problems

The world is facing significant environment problems, including global warming and worldwide energy concerns. The Fifteenth Session of the Conference of Parties to the United Nations Framework Convention on Climate Change (COP15) was held in Denmark in 2009 and global warming countermeasures were discussed by over 80 ministers. In Europe, the European Rail Research Advisory Council (ERRAC) projects were initiated to decrease CO₂ emissions to 50% by 2050, compared with...
those in 1990 (Chéron et al., 2011). Railways have received considerable attention recently as green vehicles. Fig. 1 shows CO₂ emissions of various transportation systems based on the primary energy source in Japan in 2012 (MLIT). Railways are better for the ecology than other types of transportation. Because of its outstanding ecological properties, various railway projects have been considered, such as the Shift 2 Rail project (Shift2Rail). Railways are in demand because they contribute to energy savings and reduce CO₂ emissions, compared with other types of transportation.

Some technologies have been developed to achieve energy savings in operating an electric railway. The West Japan Railway Company has surveyed its regenerative energy practices and studied its effective utilisation (Yamashita et al., 2009). The Railway Technical Research Institute develops on-board storage devices to stock regenerative energy without regeneration cancellation in Japan (Ogasa, 2009). Storage devices consisting of batteries and supercapacitors have been installed in a substation in Korea (Lee et al., 2011). Software technologies have also been proposed, such as driving operation (Albrecht, 2014). Energy-saving operation, which is considered to mean fully use of electric brakes has been tested by some railway companies (Hamazaki, 2012; Izeki, 2013).

1.2. Purpose of this study

The purpose of this study was to develop a software-based approach to achieving energy savings in railway operations by less costly means than through hardware enhancements. Previous studies have proposed the use of power-limiting brakes (Watanabe et al., 2013a, 2013b). The energy-saving efficiency of this braking method has been demonstrated. However, the performance of this braking method has been limited by the difficulty of notch operation by a driver, even if an operation assistance system has been installed (Watanabe and Koseki, 2014; Watanabe et al., 2014). For this reason, the use of automatic train operation (ATO) systems has been proposed as means to achieve better performance and energy-saving efficiency from power-limiting brakes.

In this paper, we propose an energy-saving operation scheme and a method for designing an optimised railway line schedule for ATO. The use of power-limiting brakes with ATO and the utility of its use on ATO railroad are discussed in Section 2. Our optimisation of a schedule based on ATO with power-limiting brakes and the method for determining an optimal schedule are described in Section 3. The optimisation procedure seeks to minimise the energy consumption of rolling stock so that the running time distribution based on energy saving driving between all stations is optimised while the total running time is kept constant. Practical scheduling concerns, such as the need to determine running times as integer values, are considered in the calculation procedure. Based on the optimisation procedure, we compared running curves and schedules from the point of view of energy savings, as described in Section 4. A basic schedule and an optimised schedule were compared and evaluated in terms of the total energy consumption of each.

2. Energy-saving operation for ATO

2.1. Running curve with optimisation

In terms of software applications, driving methods have been widely studied in railway research. Previous research has suggested that railway operation involves a trade-off between the energy consumption of rolling stock and running time (Bocharnikov et al., 2010). The energy consumption of rolling stock can be calculated using a running curve. For this reason, in the past, optimisation of running curves was studied for energy-saving operation purposes (Ko et al., 2005; Miyatake, 2011;
Doan et al., 2014). These studies suggested that an optimised running curve consists of maximum power acceleration, coasting, and maximum power deceleration without constant-speed running. Curves (a) and (b) in Fig. 2 are running curves without coasting and with coasting, respectively, under a fixed time constraint. The reason that the running time is constrained in the optimisation is to take into consideration the scheduling for subsequent sections along the railway line. In Fig. 2, energy consumption in the case of curve (b) is smaller than that in the case of curve (a). For this reason, a running curve optimised in the manner of curve (b) in Fig. 2 was used in this study.

2.2. Power-limiting brakes for regeneration cancellation

In recent years, rolling stock has been equipped with regenerative brakes. This technology is important to energy-saving railway operations because regenerative energy can be reused by other rolling stock and can decrease total energy consumption. However, regenerative brakes cannot decelerate rolling stock as well as mechanical brakes. Fig. 3 shows the relationship between deceleration and speed for each type of brake. Regenerative brakes cannot provide much braking power in high-speed areas, so cooperative brakes, which consist of regenerative and mechanical brakes, are often used in operation.

From the perspective of optimisation, maximum power braking is better for energy saving. However, cooperative brakes cannot regenerate as much energy when rolling stock runs at high speeds. For this reason, two brake patterns were analysed (Watanabe et al., 2013a, 2013b).

(I) Running Curve with Hybrid Cooperation between Mechanical and Electrical Brakes

This mode involves the use of cooperative brakes and is illustrated by curve I in Fig. 4. This mode can reduce the notch-off speed (which turns off an acceleration) under a fixed time constraint because high braking power can be achieved with cooperative breaks. Recently, priority use of regenerative brakes has been employed with this brake control mode.

(II) Running Curve with Power-Limiting Brakes for the Best Use of Electric Brakes

This mode involves the use of regenerative brakes only and is illustrated by curve II in Fig. 4. In this mode, the braking control depends on the braking ability of the regenerative brakes, as shown in Fig. 3. This operation increases the regenerative energy but requires higher notch-off speeds because the brake power is weaker than that of mode I at high speeds.

2.2.1. Priority use of power-limiting brakes

The main purpose of this study was to evaluate the contribution of power-limiting regenerative brakes to energy savings. Fig. 5 shows numerical results for the relationship between running time and energy consumption of a train. Power-limiting brakes (functioning as indicated by curve II in Fig. 4) result in lower energy consumption in many cases when regenerative braking is effectively used, except for very short running times.

Fig. 2. Running patterns with and without coasting.
2.2.2. Regeneration cancellation

Generally speaking, electrical energy cannot be stored, so regeneration cancellation often occurs, particularly in DC-electric railways, because of their light loads and short-interval electrical catenary sections. For such situations, analytical

![Fig. 3. Relationship between deceleration and speed for each type of braking.](image)

![Fig. 4. Two running patterns obtained using different type of brakes.](image)

![Fig. 5. Relationship between running time and energy consumption.](image)

2.2.2. Regeneration cancellation

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studies (Watanabe et al., 2013a, 2013b) and on-track tests (Watanabe and Koseki, 2014; Watanabe et al., 2014) have demonstrated the feasibility of using power-limiting brakes.

2.3. Difficulty of energy-saving driving in manual operation and advantage of ATO

Previous studies have demonstrated the usefulness of power-limiting brakes. However, the use of power-limiting brakes faces two fundamental problems, as discussed previously. The use of an ATO system with power-limiting breaks is a means to improving performance and energy-saving efficiency (Watanabe and Koseki, 2014; Watanabe et al., 2014).

(1) Difficulty in Finite Step Notch Operation

It is difficult for human drivers to perform power-limiting braking actions according to the regenerative performance curve shown in Fig. 3. To address this problem, on-board assistance systems consisting of monitors, speaker, and computers have been developed to assist drivers. However, this method has some limitations, such as notch steps. Based surveys of drivers in on-track tests, the feasible number of notch steps is limited to five, as shown in Fig. 6(a).

(2) Delay of Driver’s Action and Braking Hardware

On-track tests have shown that operational delay consists of a human driver’s delay between responding to an operation assistance order to brake and activating braking. This delay is illustrated in Fig. 6(a). To address this problem, assistance algorithms based on prediction of train motions have been employed using on-board computers. However, these algorithms’

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Fig. 6. Differences in energy-saving operation, considering notches and operating delay.
parameters are affected by human characteristics and car performance. For this reason, the parameter values should be adjusted for each driver and car.

2.4. Advantages of ATO in energy-saving operation

In ATO, there are no human drivers; the railway car is controlled by on-board computers, as shown in Fig. 6(b). This system reduces delay and increases the number of notch steps to more than 20 so that energy-saving operation based on the use of power-limiting brakes is accomplished effectively. In addition, energy regeneration is increased in comparison to a human driver’s notch operation.

Drivers maintain running times very strictly in Japan. However, it is difficult for drivers to meet running times with accuracies on the order of seconds. A running curve changes from the pre-designed curve when the running time changes. When this occurs, optimised energy-saving operation cannot be strictly achieved. In ATO, all operations are controlled by an on-board computer. Energy-saving operation is thus achieved easily and accurately.

3. Energy-saving train scheduling

3.1. Proposals of energy-saving train scheduling based on ATO

A railway timetable is a schedule developed by railway companies to manage rolling stock and transport passengers efficiently. Passenger service is considered the priority in scheduling. In addition, drivers maintain running times between stations very strictly in Japan. However, there is ever-increasing interest in ways to save energy, as mentioned in Section 1. A method for achieving energy savings in scheduling has been reported in previous studies (Ko et al., 2005). The literature (Miyatake, 2011) provides more details on the technique involved. However, this method has some limitations, such as the need to solve a differential equation and the fact that a decimal-point value, rather than an integer value, is obtained as a result. In this study, we used this method but modified it to obtain more practical results, such as integer running times and energy savings determined on the basis of the use of power-limiting brakes. A running curve was designed as described in Section 2 and is shown as curve II in Fig. 4.

3.2. Design method (Miyatake, 2011)

3.2.1. Basic approach

Previous research has suggested that railway operation is a trade-off between energy consumption and running time, as mentioned in Section 2.1 (Bocharnikov et al., 2010). In this study, we followed the design method described in the literature (Miyatake, 2011), which is explained below.

The basic approach is to change the running time in every section without changing the total running time. This means that energy consumption in every section is changed to minimise the total energy consumption. The steps in the process are as follows:

Step 1 Calculate the relationship between energy consumption and running time for each section, as shown for Sections 1–3 in Fig. 7.
Step 2 Differentiate each curve of each section.

Fig. 7. Relationships between energy consumption and running time and differentiated values for three sections.
Step 3 Choose the same differentiated value for each section, marked by circles in Fig. 7. The differentiated value can be determined from the total running time limitation. The differentiated value decreases when the total running time increases.

3.2.2. Problems with the basic approach

As mentioned in Section 3.1, the basic approach has two problems, described below.

(A) The basic approach involves solving an optimisation problem. There are some optimisation tools available (e.g., dynamic programming, calculus of variations, mixed integer programming, etc.) but it is difficult to apply differential equations to the problem of finding the best solution because the relationship between energy consumption and running time cannot be transformed into a linear function. In addition, these relationships are generally discrete functions.

(B) The basic approach requires solving a differential equation. The result obtained is some decimal-point value, not an integer value. The approach needs to be improved to accomplish scheduling in a practical manner with integer values of running times between stations.

3.3. Application to practical train scheduling

3.3.1. Proposed method

To address the first problem described in Section 3.2, parameters are defined as shown in Table 1, and a proposed solution method consisting of the following steps is employed:

Step 1 Calculate the running curve based on energy-saving operation. $E_i$ and $t_i$ are determined.

Step 2 Change the notch-off speed and calculate the running curve. Energy consumption and running time will change.

Step 3 Plot a graph, as shown in Fig. 8(a), with $t_i$ on the x axis and $E_i$ on the y axis.

Step 4 Differentiate $E_i$ with respect to $t_i$, as shown in Fig. 8(b) and Equation (1), i.e., calculate the slope of the straight line that can be drawn between any two points.

Step 5 Plot each $\theta_i$ and $t_i$ value on a graph with $\theta_i$ on the x axis and $t_i$ and $T$ on the y axis, as shown in Fig. 8(c).

Step 6 Calculate the sum of the $t_i$ values for each $\theta_i$, as indicated by the diamonds in Fig. 8(c).

Step 7 Given the limitation on the total running time $T$, determine the optimal running time $t_i$ in each section, as shown in Fig. 8(d).

$$\theta_i = \frac{\partial E_i}{\partial t_i}.$$  

(1)

$$\sum_{i=0}^{n} t_i = T.$$  

(2)

To address the second problem described in Section 3.2, we first need to define what “practical” means in the context of this study. We defined “practical” to mean addressing the practical consideration of determining running times as integer value. The optimal running time is not an integer according to the method described previously. To satisfy the practical requirement for an integer-value running time, we introduced the following modification to the procedure.

Step 1 Round the optimal running time to an integer value. The total running time $T$ is changed to $T'$.

Step 2 Focus on the total running time.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters in the calculation model.</td>
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<td>Notation</td>
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</tr>
<tr>
<td>$t$</td>
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<tr>
<td>$n$</td>
</tr>
<tr>
<td>$T$</td>
</tr>
<tr>
<td>$\theta_i$</td>
</tr>
<tr>
<td>$\Theta$</td>
</tr>
</tbody>
</table>
(1) If $T = T'$, the running time has been optimised.
(2) If $T > T'$, return to the rounding step and check the first decimal place. Choose the largest energy time sensitivity and add 1 s in this section.
(3) If $T < T'$, return to the rounding step and check the first decimal place. Choose the smallest energy time sensitivity and subtract 1 s in this section.

Step 3 Round the approximated optimal running time to an integer value again. Repeat Step 2(2) or Step 2(3) if $T \neq T'$

This modified method is based on previous research, as mentioned in Section 2 (Bocharnikov et al., 2010). Energy consumption is reduced when a longer running time is allowed.

4. Simulation analysis for energy-saving scheduling

4.1. Objectives and conditions

The main objective of the simulation conducted in this study was to evaluate the energy-saving effect of optimising the running time in each section, based on energy-saving operation, as illustrated in Fig. 9. The energy-saving effect from step 1 to step 2 has been investigated in previous studies (Watanabe et al., 2013a, 2013b; Watanabe and Koseki, 2014; Watanabe et al., 2014). The following discussion is focused on steps 2 and 3 and verification of the advantage of the proposed optimisation method.
Table 2 shows the simulation conditions considered. These conditions were based on an existing railway. Ten sections that have no speed limitations were chosen for application of energy-saving operation, consisting of acceleration, coasting, and deceleration without reacceleration.

4.2. Calculation results

Fig. 10 shows the relationship between $T$, the total running time, and $\Theta$, the common energy–time sensitivity in all sections. The relationship of $T$ to $\Theta$ is a discontinuous function that is approximated as a continuous function. When the upper limit of the total running time $T$ is 713 s, the optimal common energy–time sensitivity $\Theta$ is determined from Fig. 10 to be 0.1525. Table 3 shows the optimal running time in each section calculated using the proposed method, modified as described in Section 3.3. The centre line of $t_i$ values is the basic running time determined by the railway company. The highlighted values are the optimal running times $t_i$ determined from Equation (3).

$$\theta_i = \Theta.$$  \hfill (3)

4.3. Energy-saving effects

Fig. 10 and Table 3 show that the running times of all sections are changed and optimised. Table 4 shows the energy-saving effects of applying the optimisation procedure. According to Table 4, 1.00 kWh of energy is saved per one-way trip. This railway has 153 trains running on it every weekday. The total annual savings in energy consumption achieved are 111.7 MWh, assuming that 153 trains run every day and 1.00 kWh is saved in each one-way trip.

5. Conclusions

In previous research, energy-saving railway operation methods have been compared, and the significance of ATO to energy savings has been evaluated. Energy-saving railway operation consists of maximum power accelerating, coasting, and maximum power decelerating. It has been proven that it is better to use only regenerative braking for train deceleration in many cases. This braking method is called power-limiting braking. On-track tests have confirmed the energy-saving effects achievable by optimal use of regenerating braking. Experimental results show that power-limiting braking is effective and feasible for energy saving in human-operated railways. However, greater energy savings can be achieved with ATO than with manual train operation. Therefore, energy-saving ATO system design was examined in this study. We focused on the optimisation of running time in track sections between stations because ATO can achieve a theoretically optimal train running profile. Optimised running times by section were modified to adopt requirements of practical scheduling and yield energy saving effects in this study. A conventional train scheduled and one developed using the proposed method were compared.
For the railway considered in the simulation, optimal train operation was found to be able to reduce energy consumption by 1.9% per one-way trip over ten sections, for the same total running time. The proposed method focuses only on the optimisation of running time; additional timetabling strategies for saving energy, such as reducing dwell and turnaround times and increasing running time margins, can also be applied.

Table 3
Optimal running time for each section from a practical point of view.

<table>
<thead>
<tr>
<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
<th>Section 5</th>
<th>Section 6</th>
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The highlighted values indicate optimal running times.

Table 4
Analysis of energy consumption.

<table>
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<th>Cases</th>
<th>Basic</th>
<th>Optimised</th>
</tr>
</thead>
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<td>Total running time</td>
<td>713 s</td>
<td>713 s</td>
</tr>
<tr>
<td>Changed sections</td>
<td>–</td>
<td>10</td>
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<tr>
<td>Energy consumption</td>
<td>53.40 kWh</td>
<td>52.40 kWh</td>
</tr>
<tr>
<td>Energy savings</td>
<td>–</td>
<td>–1.00 kWh</td>
</tr>
<tr>
<td>Percent energy savings</td>
<td>–</td>
<td>–1.9%</td>
</tr>
</tbody>
</table>

For the railway considered in the simulation, optimal train operation was found to be able to reduce energy consumption by 1.9% per one-way trip over ten sections, for the same total running time. The proposed method focuses only on the optimisation of running time; additional timetabling strategies for saving energy, such as reducing dwell and turnaround times and increasing running time margins, can also be applied.
6. Future work

The case study considered in this paper had no speed limitations. A case involving sectional speed limits is under study. The energy-saving effect of optimal train operation will be evaluated by comparison with conventional operation for this and other practical cases.

References


