Energy-Saving Train Scheduling Diagram for Automatically Operated Electric Railway

Shoichiro WATANABE (Ph.D. Candidate)
Takahumi KOSEKI (Professor)

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Oral Session: Energy-efficient driving and driver advisory systems
Outlines

• Introduction & Purpose

• (1) Energy-Saving Operation for A Train
  • Power-limiting Brake
  • Advantages of ATO

• (2) Energy-Saving Train Scheduling
  • Basic Approach
  • Application to Practical Train Scheduling with Proposed Methods

• Analysis for Energy-saving Scheduling

• Conclusions & Future Work
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• Conclusions & Future Work
• A Key to Solving Environment Problems

• Some technologies have been developed
  • Hardware side ➔ Storages, Power device, Conversion control

• Software side
  
  (1) **Energy-saving operation**
  Optimal energy-saving running curve between two station ➔ Best use of regenerative braking with ATO

  (2) **Energy-saving scheduling**
  Optimisation to change running time between every pairs of stations based on (1) Energy-saving operation
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Energy-saving operation\(^{(11)}\) was

i. Restriction of **running time** for scheduling

ii. Max accelerating, coasting and **power-limiting braking**

The best use of the regenerative brakes

The diagram shows relationships of energy consumption:

\[ A < B \]

Advantages of ATO in Operation

- The railway car is controlled by on-board computers
  1. Install optimised energy-saving operation in ATO

- ATO system can keep running times with accuracies on the order of seconds
  2. Design the optimised schedule between every pairs of stations based on this energy-saving operation
Advantages of ATO in Operation

- The railway car is controlled by on-board computers
  - (1) Install optimised energy-saving operation in ATO

- ATO system can keep running times with accuracies on the order of seconds
  - (2) Design the optimised schedule between every pairs of stations based on this energy-saving operation

How to design the optimised schedule based on (1) energy-saving operation?
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Basic Approach – Change The Running Time –

**Conventional schedule**

**Running time**
- Station A: 60 sec
- Station B: 60 sec
- Station C: 120 sec
- Station D: 180 sec

**Optimal schedule**

**Running time**
- Station A: 50 sec
- Station B: 80 sec
- Station C: 130 sec
- Station D: 50 sec

**Energy-Saving**

**Total running time is not changed**
Basic approaches\(^{(15)}\) are as follows:

1. Calculate the relationship between energy consumption and running time for each section.
2. Differentiate each curve of each section.
3. Choose the same differentiated value for each section.

The result obtained is some decimal-point value.

Accomplish scheduling in a practical manner with \textbf{integer value}.

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• Calculate the running curve based on energy-saving operation.
• Energy consumption $E_i$ and running time $t_i$ in the $i$-th section are determined.
• **Change the notch-off speed** and calculate the running curve.

• $E_i$ and $t_i$ in the $i$-th section will **change**.

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### Step-by-Step Procedure

**Step 1**
- Calculate $E_i$ & $t_i$

**Step 2**
- Change notch-off speed

**Step 3**
- Plot $E_i$ & $t_i$

**Step 4**
- $\theta_i = \frac{\partial E_i}{\partial t_i}$

**Step 5**
- Plot $\theta_i$ and $t_i$

**Step 6**
- Sum up a total running time $T$

**Step 7**
- Determine the optimal running time $t_i$
• Plot a graph with $t_i$ on the x axis and $E_i$ on the y axis.

**Step 1**
- Calculate $E_i$ & $t_i$

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- Determine the optimal running time $t_i$
Differentiate energy consumption with respect to running time

Calculate the slope of the straight line that can be drawn between any two points.

\[ \theta_i = \frac{\partial E_i}{\partial t_i} \] is energy time sensitivity in the \( i \)-th section.

\[ \theta_i = \frac{\partial E_i}{\partial t_i} \]

**Steps**

**Step 1**
- Calculate \( E_i \) & \( t_i \)

**Step 2**
- Change notch-off speed

**Step 3**
- Plot \( E_i \) & \( t_i \)

**Step 4**
- \( \theta_i = \frac{\partial E_i}{\partial t_i} \)

**Step 5**
- Plot \( \theta_i \) and \( t_i \)

**Step 6**
- Sum up a total running time \( T \)

**Step 7**
- Determine the optimal running time \( t_i \)
Practical Scheduling with Proposed Methods

- Plot each $\theta_i$ and $t_i$ value on a graph with $\theta_i$ on the x axis and $t_i$ on the y axis

Step 1
- Calculate $E_i$ & $t_i$

Step 2
- Change notch-off speed

Step 3
- Plot $E_i$ & $t_i$

Step 4
- $\theta_i = \frac{\partial E_i}{\partial t_i}$

Step 5
- Plot $\theta_i$ and $t_i$

Step 6
- Sum up a total running time $T$

Step 7
- Determine the optimal running time $t_i$
Calculate the sum of the $t_i$ values for each $\theta_i$

- The summation of $t_i$ is a total running time $T$.
- $\theta$ is common energy time sensitivity for all sections.

**Steps**

- **Step 1**
  - Calculate $E_i$ & $t_i$

- **Step 2**
  - Change notch-off speed

- **Step 3**
  - Plot $E_i$ & $t_i$

- **Step 4**
  - $\theta_i = \frac{\partial E_i}{\partial t_i}$

- **Step 5**
  - Plot $\theta_i$ and $t_i$

- **Step 6**
  - Sum up a total running time $T$

- **Step 7**
  - Determine the optimal running time $t_i$
● Given the limitation on the total running time $T$
● Determine the optimal running time $t_i$ in each section

Graphical representation:
- $T$: Summation (the function of $\Theta$)
- $t_i$: Section (the function of $\theta$, $i = 3$)
- $t_i$: Section (the function of $\theta$, $i = 2$)
- $t_i$: Section (the function of $\theta$, $i = 1$)

Legend:
- $\theta_i = \frac{\partial E_i}{\partial t_i}$

Equations:
- $\theta_i$: Energy Time Sensitivity of the $i$-th Section
- $\Theta$: Common Energy Time Sensitivity for All Sections

Steps:
1. Calculate $E_i$ & $t_i$
2. Change notch-off speed
3. Plot $E_i$ & $t_i$
4. $\theta_i = \frac{\partial E_i}{\partial t_i}$
5. Plot $\theta_i$ and $t_i$
6. Sum up a total running time $T$
7. Determine the optimal running time $t_i$
Round the optimal running time to an integer value. The total running time $T$ is changed to $T'$.  

- Choose the largest energy time sensitivity and add 1 s in this section.  
- Choose the smallest energy time sensitivity and subtract 1 s in this section.

START

$T > T'$

FINISH
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## Calculation Conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Remarks column</th>
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<td>DC 1650 V</td>
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- 4M0T: Load-compensating device is considered
- Not a round trip
- Platform doors are installed
- In acceleration
- In regeneration
Results of Common Energy Time Sensitivity

$\Theta$: Common Energy Time Sensitivity for All Sections

$T$: Total Running Time (sec)

- Point at $\Theta = 0.1525$ and $T = 713$ sec
Optimal Running Time from a Practical Point of View.

<table>
<thead>
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<th>Section 1</th>
<th>Section 2</th>
<th>Section 3</th>
<th>Section 4</th>
<th>Section 5</th>
<th>Section 6</th>
<th>Section 7</th>
<th>Section 8</th>
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</table>

The image shows a graph with a red arrow pointing to the value 0.1525.
## Analysis of Energy Consumption

<table>
<thead>
<tr>
<th>Cases</th>
<th>Basic</th>
<th>Optimised</th>
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<tbody>
<tr>
<td>Total running time</td>
<td>713 s</td>
<td>713 s</td>
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<tr>
<td>Changed sections</td>
<td>-</td>
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<tr>
<td>Energy consumption</td>
<td>53.40 kWh</td>
<td>52.40 kWh</td>
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<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>
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Conclusions & Future Work

Conclusions

• (1) Energy-saving railway operation
  • Power-limiting braking

• (2) Energy-Saving train scheduling
  • Optimisation of running time in track sections between stations
  • Practical scheduling method

• Analysis for Energy-saving Scheduling
  • Energy saving effects : 1.9%

Future Work

• Additional timetabling strategies for saving energy
  • Reducing dwell and turnaround times and increasing running time margins
Thank you very much for your attention.

Shoichiro WATANABE

The University of Tokyo
shoichiro@koseki.t.u-tokyo.ac.jp