A Practical Algorithm for Energy-Saving Train Running Profile Generation

Tatsunori Suzuki
Toshiba Corporation, Japan

Collaborators
Leandro Lopez Toshiba Corp.
Junko Ohya Toshiba Corp.
Yukinori Tonosaki Toshiba Corp.

March 26, 2015  RailTokyo2015

© 2015 Toshiba Corporation
Introduction

Majority of railway energy consumption is from traction → requires a lot of investment and replacement

Eco-driving can reduce energy consumption without huge investments.
→ need more **practical methods for** generating energy-efficient running profiles

Proposed algorithm
General policy for eco-driving

Energy-saving speed profiles generally:
  1. Accelerate at full power
  2. Reduce the maximum speed
  3. Increase coasting time
  4. Brake at lower speeds
Formula of Trainset motion

\[
\frac{dx(t)}{dt} = v(t)
\]

\[
M \frac{dv(t)}{dt} = F[v(t), u(t)] - R[x(t), v(t)]
\]

- \( t \): the time since the departure from the start point
- \( x(t) \) and \( v(t) \): the distance and velocity as a time \( t \)
- \( F[v(t); u(t)] \): the tractive effort
- \( R[x(t); v(t)] \): the overall resistance
- \( u(t) \): the notch (acceleration and deceleration level)
- \( M \): the trainset weight
Formula of Objective function

The energy consumption of the trainset:

\[
J = \int_0^T I[v(t), u(t)] \cdot V[v(t), u(t)] dt
\]

\[
= \begin{cases} 
\int_0^T I[v(t), u(t)] \cdot V_1 dt & (I[v(t), u(t)] > 0) \\
0 & (I[v(t), u(t)] = 0) \\
\int_0^T I[v(t), u(t)] \cdot V_2 dt & (I[v(t), u(t)] < 0)
\end{cases}
\]

- \( I[v(t); u(t)] \) : the electric motor current
  - positive value : the current during normal powering
  - negative value : the current flow when the motor acts as an energy generator.

- \( V_1, V_2 \) : the line voltage during acceleration and braking
Formula of Minimum-energy control problem

\[ \min. \ J \]

s.t. \[ \frac{dx(t)}{dt} = v(t), \]

\[ M \frac{dv(t)}{dt} = F[v(t),u(t)] - R[x(t),v(t)], \]

\[ x(0) = 0, \ v(0) = 0, \] \hspace{1cm} (1)

\[ x(T) = X, \ v(T) = 0, \] \hspace{1cm} (2)

\[ 0 \leq v[x] \leq V[x] \] \hspace{1cm} (3)

(1) : the initial conditions
(2) : the terminal conditions
(3) : the maximum speed limit with respect to distance
\( T \) : the running time
\( X \) : the distance between the two stations
Multi-stage decision problem

- Combinatorial optimization
- Decision-making of notch number at each time
- When the number of notch is 10 and running time is 100[sec], the number of solutions is $10^{100}$.

Need an efficient pruning algorithm
Proposed Method

• **Two main steps**
  1. Solve the minimum-time control problem
  2. Solve the minimum-energy control problem

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Stations</td>
<td>• Speed</td>
</tr>
<tr>
<td>• Speed limits</td>
<td>• Notch time series</td>
</tr>
<tr>
<td>• Gradient</td>
<td>• Position</td>
</tr>
<tr>
<td>• Curve radius</td>
<td>• Energy consumption</td>
</tr>
</tbody>
</table>

START

Generate the minimum-time running profile (i.e., solve the minimum-time control problem)

Generate the minimum-energy running profile (i.e., solve the minimum-energy control problem)

END
Solve the minimum-time control problem

\[
\min . \, T = \min . \frac{X}{\bar{v}} \rightarrow \max . \bar{v} \approx \max . \frac{x(t)}{t}
\]

Change the Objective function

\[ J : \text{Energy} \]
\[ T : \text{Running time} \]
Solve the minimum-energy control problem

- Pruning criteria:
  1. Position \( x_l(t) \leq x_{\text{opt}}(t) \leq x_u(t) \)

  - Distance
    - minimum-time running profile

  - Objective running profile
    - Time

  - Position
    - \( x_l(t) \)
    - \( x_u(t) \)
    - \( x_{\text{opt}}(t) \)

  - Speed
    - \( v_{\text{opt}}[x] \leq v_u[x] \)

Generate the minimum-time running profile (i.e. solve the minimum-time control problem)

Generate the minimum-energy running profile (i.e. solve the minimum-energy control problem)

START

END
Solve the minimum-energy control problem

3. Quantization

Keep minimum energy solution in each mesh area
**Pruning and generating image**

1. Branching (t = 1)

2. Pruning (t = 1)

3. Branching (t = 2)

State 1’s energy is smaller than state 3’s one.

Notch operation

Driving pattern

Speed limit violation

Energy optimization

Timetable rule violation

Time Table rule violation

Energy optimization

Notch operation

Driving pattern

Speed limit violation

Energy optimization

Timetable rule violation

State 1’s energy is smaller than state 3’s one.

Notch operation

Driving pattern

Speed limit violation

Energy optimization

Timetable rule violation

State 1’s energy is smaller than state 3’s one.

Notch operation

Driving pattern

Speed limit violation

Energy optimization

Timetable rule violation

State 1’s energy is smaller than state 3’s one.
Sample of running profile for eco-driving

minimum time running profile  
constant velocity running profile  
energy-saving running profile  

gradient

position [m]  
velocity [m/sec]
### Results of proposed algorithm

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MTRP</td>
<td>100</td>
<td>18.25</td>
<td>30.00</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>CVRP</td>
<td>105</td>
<td>13.85</td>
<td>25.50</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>ESRP</td>
<td>105</td>
<td>13.29</td>
<td>26.91</td>
<td>11.7</td>
</tr>
</tbody>
</table>

- **MTRP**: Minimum-Time Running Profile
- **CVRP**: Constant-Velocity Running Profile
- **ESRP**: Energy-Saving Running Profile
Toshiba’s Trial Run / Achievements

1. Toshiba’s Trial:
   To check the performance of Toshiba’s eco-running profile, Toshiba conducted an eco-driving trial on CP Porto Caíde Line with the support from Nomad Tech and CP Porto on December 2013.

2. Achievements:
   - Energy savings of about 10%, compared to the current driving method
Trial Run (Conditions)

1. **Trial section**
   - Between Ermesinde station and Caíde station.

2. **Same trainset and trips**
   - Trainset 3408
   - Same 6 trips (3 trips bound for Ermesinde, the other 3 for Caíde)

3. **Same drivers**
   - One for AM shift and another one for PM shift
Result of Trial run

For Ermesinde (Down hill)

- Past ave: 102.8 kWh
- Ave: 83.7 kWh

Average savings 17% (10~23%)

For Caíde (Up hill)

- Past ave: 201.48 kWh
- Ave: 193.6 kWh

Average savings 6% (1~10%)

6% reduction
Conclusion

The proposed algorithm has been proven to efficiently generate energy-saving running profiles through actual trial runs, which yielded an average of 10% savings in energy consumption.

Further developments include adopting the algorithm for:
- Real-time train control applications
- ATO (Automatic Train Operation) systems
- Driver training systems / simulators