Running time supplements: energy-efficient train control versus robust timetables

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**Introduction**

**Current situation at NS**

- **EETC (energy-efficient train control):** min. tot. traction energy by using running time supplements in timetable

- **UZI method (Universal energy-efficient driving idea):** an EETC method applied by NS

- **Method:** accelerate as fast as possible and start coasting

- **Problem:** tightening the timetable + rounding to whole minute

<table>
<thead>
<tr>
<th>Short distance</th>
<th>Long distance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Running time [min]</strong></td>
<td><strong>Coasting speed [km/h]</strong></td>
</tr>
<tr>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>110</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
</tr>
<tr>
<td>7</td>
<td>130 (not for SGM)</td>
</tr>
<tr>
<td>8</td>
<td>140 (not for SGM)</td>
</tr>
</tbody>
</table>
Introduction
Problem description

• EETC isn’t integrated very well in the timetable design process in NL

• Objective: develop model that calculates optimal
  – Coasting point
  – Cruising speed
  – Running time supplement distribution
Method
Driving strategies (1/3)

• Running time of a train is influenced by:
  – Infrastructure characteristics
  – Rolling stock characteristics
  – Timetable
  – External influences

• Train behavior/driving regimes:
  1. Acceleration
  2. Cruising
  3. Coasting
  4. Braking
Method
Driving strategies (2/3)

- Time-optimal/technical minimum running time: as fast as possible given distance
Method
Driving strategies (3/3)

- Energy-efficient train control or EETC: min. tot. traction energy given distance and available time
Method
Algorithm (1/3)

- Optimal control problem (min. total traction energy with control $u^+(x) = \max(u(x), 0)$)

\[
\min_u E_{\text{mech}}(v, u) = \int_0^x u^+(x)dx
\]

- Subject to

\[
\frac{dt}{dx} = \frac{1}{v(x)}
\]

\[
\frac{dv}{dx} = \frac{F(x) - R(v(x))}{v \cdot \rho \cdot m} = \frac{u(x) - r(v)}{v}
\]

$t(0) = t_0, t(X) = T, \quad v(0) = v_0, v(X) = v_X$

$v(x) \in [0, v_{\text{max}}(x)], \quad u(x) \in [-u_{\text{min}}(v(x)), u_{\text{max}}(v(x))]$
Method
Algorithm (2/3)

- Hamiltonian $H(t, v, \lambda, \phi, u)$ consists of co-state variables $\lambda(x)$ and $\phi(x)$

\[
H(t, v, \lambda, \phi, u) = -u^+ + \lambda \cdot \left( \frac{u}{v} - \frac{r(v)}{v} \right) + \frac{\phi}{v}
\]

- Optimal control $\hat{u}(x)$: use Pontryagin Maximum Principle (PMP) by max. Hamiltonian which leads to

\[
\hat{u}(x) = \begin{cases} 
  u_{\text{max}}(x) & \text{for } \lambda(x) > v(x) \quad \text{(Maximum acceleration)} \\
  [0, u_{\text{max}}(x)] & \text{for } \lambda(x) = v(x) \quad \text{(Cruising)} \\
  0 & \text{for } \lambda(x) < v(x) \quad \text{(Coasting)} \\
  -u_{\text{min}}(x) & \text{for } \lambda(x) \leq 0 \quad \text{(Maximum braking)}
\end{cases}
\]
Method
Algorithm (3/3)

- Algorithm based on results PMP has been built in MATLAB

- Algorithm (EZR model) iteratively determines per section:
  - Optimal coasting point (bisection method)
  - Optimal cruising speed (Fibonacci method)
Method

Case study

Case study:
• Apply EZR model results (2012 timetable)
• Train line Utrecht Centraal (Ut) – Rhenen (Rhn) in NL
• Including varying gradient profile
• Without regenerative braking energy
• Rolling stock type SLT of NS
Case study
Timetable 2012

Results timetable 2012 Ut-Har and Har-Rhn

[Graphs showing SLT VI speed profile over distance on line Ut-Har and Har-Rhn, with labels for Time-optimal, Energy-efficient, and UZI method.]
Case study
Uniformly redistribute running time supplements

- Uniformly redistribute running time supplements without hinder for surrounding trains
- Results uniform redistribution Ut-Har and Har-Rhn

![SLT VI speed profile over distance on line Ut-Har](image)

![SLT VI speed profile over distance on line Har-Rhn](image)

- Time-optimal
- Energy-efficient
- UZI method
Case study
Summary main results

- Allocating time allowances towards destination station leads to higher energy consumption costs than a uniform allocation.
- Optimal energy-efficient driving in existing timetable is still worse than UZI method in timetable with uniform time allowances.
- First optimize timetable then focus on train control (with higher investments).

<table>
<thead>
<tr>
<th>Timetable</th>
<th>UZI method</th>
<th>Energy-efficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing</td>
<td>64.6 kWh (12.1%)</td>
<td>83.9 kWh (15.7%)</td>
</tr>
<tr>
<td>Uniform</td>
<td>84.7 kWh (15.9%)</td>
<td>116.1 kWh (21.8%)</td>
</tr>
</tbody>
</table>

Energy savings compared to time-optimal driving strategy.
Case study
Real-time application EZR model

- Model results were applied real-time (only once)
- Driving strategy EZR model is feasible in reality
- Rolling stock characteristics are possibly too conservative:
  - Train resistance
  - Brake settings for ATP (Automatic Train Protection) system
Conclusions

• Energy-efficient train control model (EZR model) has been developed and applied real-time

• Model results for case study (Ut-Rhn):
  – Allocating time allowances towards destination station leads to higher energy consumption costs than a uniform allocation
  – Optimal energy-efficient driving in existing timetable is still worse than UZI method in timetable with uniform time allowances

• First optimize the timetable then focus on EETC
Questions?

Thank you for your attention!

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