Energy efficiency in rail operation
From train driving to railway traffic control

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Publication Date:
2017-12

Permanent Link:
https://doi.org/10.3929/ethz-b-000218994

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ENERGY EFFICIENCY IN RAILWAY OPERATION: FROM TRAIN DRIVING TO RAILWAY TRAFFIC CONTROL

Dr. Valerio De Martinis
Outline

• Introduction
  o General considerations
  o Energy efficiency in railway operation
  o Passenger trains vs Freight trains

• Modeling energy efficiency into rail operation
  • Modeling the system…
  • Speed profile optimization
    • examples
  • Rescheduling models
    • examples

• An outlook to future requirements: Dynamic capacity optimization

• Conclusion
Introduction
General considerations

- Rail transport is eco-friendly

How can rail systems keep their performances and at the same time satisfy possible increases of traffic?

Shift from road to rail?

- New infrastructures
  Expensive, “grey” energy, no clear payback.
- Tighter schedules
  Reduced buffer times, higher speeds. More conflicts.
- Longer, heavier trains
  Increased tractive energy needs.

Technology, and a better use of it
We focus on energy efficiency in rail operation because:

- Rail traffic in Switzerland is the highest in the world (n. of trains per route)
- Freight rail traffic is a non negligible % of rail traffic in Switzerland (≈ 20%)
- Energy efficiency in rail operation contributes to the rail competitiveness.
- Energy efficient rail operation contributes to the transition phases (e.g. switching from conventional power sources to renewable ones)
Energy efficiency in railway operation

Demand System
- Users’ needs
  - Freight
  - Passengers
- Customer satisfaction

Planning & Operation System
- Services & Timetables
- Traffic management
- Analyses & Targets
- Train control

Energy System
- On board system
- Smart grid
- Electric substations
- Public grid & Energy market

Demand system
- Punctuality
- ...

Energy system
- Features & Limits
- ...

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Energy efficiency in railway operation
Passenger trains vs Freight trains

- Higher priority
- Higher punctuality
- Higher performances
- Defined timetable and routes
- Fixed composition
- ...

- Lower priority
- Lower punctuality
- Lower performances
- Flexible departure times, stops, arrival times, routes
- Variable composition
- ...

More subjected to rescheduling
Predefined models may be unrealistic

Predefined models and operating conditions
Calibration and optimization during operation
## Literature review – strategies and solutions...

<table>
<thead>
<tr>
<th>Traffic Manag.</th>
<th>Tractive ECR</th>
<th>Net ECR</th>
<th>Better use of PSS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single train control</strong></td>
<td><strong>planning</strong></td>
<td><strong>operation</strong></td>
<td><strong>planning</strong></td>
</tr>
<tr>
<td>• Energy optimal speed profile parameters</td>
<td>• Departure and arrival synchronization (optimal use of storage systems at wayside)</td>
<td>• Energy optimal speed profile (minimization of acceleration phases)</td>
<td>• Departure and arrival scheduling</td>
</tr>
<tr>
<td>• Coasting phase introduction</td>
<td>• Energy optimal speed profile adoption and/or modification (ADL)</td>
<td>• Energy optimal speed profile adoption and/or modification</td>
<td>• Energy optimal speed profile adoption and/or modification (ADL)</td>
</tr>
<tr>
<td>• Aerodynamics</td>
<td>• Anticipating train control for conflict avoidance</td>
<td>• Anticipating train control for energy transfer between different trains/to the public grid</td>
<td>• Anticipating train control for energy transfer between different trains/to the public grid</td>
</tr>
<tr>
<td>• Departure time (Green wave)</td>
<td>• Anticipating train control for unplanned stops avoidance</td>
<td>• Departure and arrival synchronization (optimal use of storage systems at wayside)</td>
<td>• Departure and arrival synchronization (optimal use of storage systems at wayside)</td>
</tr>
<tr>
<td>• Efficient paths (short, flat,...)</td>
<td>• Rescheduling for conflict avoidance</td>
<td>• Rescheduling for conflict avoidance</td>
<td>• Rescheduling for conflict avoidance</td>
</tr>
<tr>
<td>• Energy efficient Timetabling</td>
<td>• ...</td>
<td>• ...</td>
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<tr>
<td>• ...</td>
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</tbody>
</table>
... and our expertise at IVT- ETH

**Tractive Energy Consumption Reduction**

**Traffic Management**
- Scheduling
- Rescheduling
- Anticipating train control

**Single train view**
- Speed profile optimization

**Analysis of Energy Consumption components**

**Energy Supply Management**
- Weather conditions
- Interaction with the public grid

- PhD. Gabrio Caimi
- Ambra Toletti and Valerio De Martinis
- PhD. Xiaolu Rao
- Valerio De Martinis
- Axel Bomhauer-Beins
- Axel Bomhauer-Beins, … Valerio De Martinis
Modeling energy efficiency into rail operation
Why this system?

The steel wheel - steel track contact does not provide the vehicle with enough adherence to brake, thus to drive, “at sight” like cars. Braking distances for high speed trains are of several kms. But, on the other hand, it is very energy efficient!
Modeling the system
Traffic circulation

Block section:
- Defined by two consecutive main signals
- Only one train per time (density controlled system)
- Length is computed considering braking from a reference speed until full stop (conventional conditions)
- When the train is running, it reserves the successive(s) block section(s)
- When it leaves a block section it means that it is completely outside from it.
- Blocking time.
Some assumption on timetable resources can be used for energy efficiency.

Scheduled time = Minimum + Reserve

- Time supplement for delay recovering (Running, Dwelling)
- Time supplement for avoiding delay propagation (Buffer)

How can we implement energy efficiency? First we need time availabilities …
Modeling the system
What do we need

Running Time vs. Energy Consumption

Orange markers: measurements, same track, same train, same timetable, but different drivers

Blue line: Simulation of ideal conditions, i.e. minimum energy consumption against running time.

Green Area: Expected variation by following DAS instruction

Red Area (emphasized): Expected variation by using ATO System

* Courtesy of Network Rail (2009)
Modeling the system

What do we need

- **RTR**  Running Time Reserve
- **DTR**  Dwell Time Reserve
- **B_t**  Buffer Time

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**Station A**

**Station B**

**Station C**

- **S**

- **RTR**

- **B_t**

- **DTR**

- **Scheduled running time**

- **Minimum running time**

- **Blocking time**

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Modeling the system
Speed profiles and trajectories

Planning:
- energy efficient speed profiles

Real time operation:
- speed profiles information (to drivers)
- Trains position information (to dispatchers)

Energy efficient timetables
Modeling the system
Simulation-based framework
Outline

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  • Modeling the system…
  • Speed profile optimization
    • examples
  • Rescheduling models
    • examples

• An outlook to future requirements: Dynamic capacity optimization

• Conclusion and further perspectives
The supply design modeling approach

- Control variables
  - Cruising speeds (according to variation of speed limits)

- Simulation of the system
  - Definition in time and space of the simulation process

- Supply design model
  - OF: Energy consumption minimization
  - Algorithm: GA (matlab opt toolbox)

- Constrained optimization of the system
  - Definition of time constraints for preserving train service and rail scheduling

- Performances and impacts
  - Energy consumption and delays compatible with the current traffic conditions and forecast

The supply design model

\[ [SP_{opt}] = \arg \min_{SP} E(SP) \]

**Optimization Algorithm**
- Speed profile parameters (SP)

**Speed profile definition**
- Check constraints on time and space

**Energy consumption**
- Power request, energy consumed

**Constraints on:**
- Acceleration, speeds, deceleration
- Extra time available (% of reserve times)
- Distance to cover
The simulation model

Delays, arrivals, departures, conflicts, etc.
An example on passenger trains

- Data availability
- The optimization procedure
- Speed profile optimization
An example on passenger trains

S9 course n. 18919

<table>
<thead>
<tr>
<th>Track</th>
<th>distance [km]</th>
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<tbody>
<tr>
<td>ZHB - ZSTH</td>
<td>1.745</td>
</tr>
<tr>
<td>ZSTH - STET</td>
<td>5.351</td>
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<tr>
<td>STET - DUE</td>
<td>2.659</td>
</tr>
<tr>
<td>DUE - SCWE</td>
<td>3.279</td>
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<tr>
<td>SCWE - NAEN</td>
<td>2.685</td>
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<td>NAEN - UST</td>
<td>2.679</td>
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<table>
<thead>
<tr>
<th>SBB-CFF-FFS Re 450</th>
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<td>Type and origin</td>
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<td>Power type</td>
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<td>Specifications</td>
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<td>UIC classification</td>
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<td>Gauge</td>
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<tr>
<td>Length</td>
</tr>
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<td>Locomotive weight</td>
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<td>Electric system(s)</td>
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<td>Current collection method</td>
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<tr>
<td>Performance figures</td>
</tr>
<tr>
<td>Maximum speed</td>
</tr>
<tr>
<td>Career</td>
</tr>
<tr>
<td>Operator(s)</td>
</tr>
<tr>
<td>Number(s)</td>
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</table>
Some results from first implementation

<table>
<thead>
<tr>
<th>Interstation Track</th>
<th>scenario</th>
<th>Max Speed [km/h]</th>
<th>Start coasting [m]</th>
<th>End coasting [m]</th>
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</thead>
<tbody>
<tr>
<td>STET - DUE</td>
<td>Time Optimal</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy Optimal</td>
<td>94.124</td>
<td>1.378</td>
<td>2.125</td>
</tr>
<tr>
<td>SCWE - NAEN</td>
<td>Time Optimal</td>
<td>124</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Energy Optimal</td>
<td>97.864</td>
<td>0.731</td>
<td>2.168</td>
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<tr>
<td>NAEN - UST</td>
<td>Time Optimal</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>Energy Optimal</td>
<td>86.254</td>
<td>0.524</td>
<td>1.955</td>
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</table>
Some results from first implementation

-16.7%

Time optimal
Energy saving
Some results from first implementation
An example on freight trains

- Data availability
- Timetable and optimization hypothesis
- Speed profile optimization
Data availability

BLS Re485

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>2002-2003</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>84 tons</td>
<td>Weight</td>
</tr>
<tr>
<td></td>
<td>87 mph (140km/h)</td>
<td>Max speed</td>
</tr>
<tr>
<td></td>
<td>5.6 MW (7500 hp)</td>
<td>Power class</td>
</tr>
<tr>
<td></td>
<td>18.9 m</td>
<td>Length</td>
</tr>
<tr>
<td></td>
<td>300 kN</td>
<td>Tractive effort</td>
</tr>
<tr>
<td></td>
<td>240 kN</td>
<td>Braking effort</td>
</tr>
</tbody>
</table>

(*) Hans Waegli, “Bahnprofil Schweiz”, AS Verlag 2010
Data availability

BLS trains - Basel-Domodossola via Bern

1220 tons Total weight of the train
15 Number of wagons
Timetable and optimization hypothesis
**Speed profile optimization**

Comparison between real data and energy saving (ES) results from optimization

<table>
<thead>
<tr>
<th>Energy</th>
<th>section 1</th>
<th>section 2</th>
<th>section 3</th>
<th>section 4</th>
<th>section 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>measured</td>
<td>900</td>
<td>1412</td>
<td>4195</td>
<td>6014</td>
<td>6892</td>
</tr>
<tr>
<td>optim</td>
<td>848</td>
<td>(1724)</td>
<td>3501</td>
<td>5174</td>
<td>6045</td>
</tr>
<tr>
<td>energy saved</td>
<td>-5.78%</td>
<td>(22.10%)</td>
<td>-16.54%</td>
<td>-13.97%</td>
<td><strong>-12.28%</strong></td>
</tr>
</tbody>
</table>

- Time shift at Tecknau 10 min
- Spiez + 3
- Domodossola +0

Computing time: 30s – 1.75min
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• An outlook to future requirements: Dynamic capacity optimization

• Conclusion and further perspectives
Overview of rescheduling models

FlexiblePath AG
AlternativeGraph

RCG
Retiming
FlowConservation
Reformulated
FixedPath
TimeVariables
FP
Trajectories
Reordering
Rerouting

SimultaneousRescheduling&Rerouting
BlockingTimeStairways
ConflictClique

ResourceConflictGraph

Above all: delay minimization

Energy saving is a positive effect of rescheduling procedures
Current solutions

Small conflicts resolution through detection and speed profile modification (Anticipating Train Control)

Specific energy-efficient characteristics of speed profiles as constraints for the generation of rescheduling solution (green wave corridor)

Database of possible energy efficient speed profiles and related trajectories to include in the rescheduling process
Energy efficient scheduling through the RCG approach

Ph.D. dissertation of Fuchsberger (2012)
Rescheduling through RCG approach

Multi objective rescheduling through the RCG approach

Current solutions
Decision variables (1)

- Based on the blocking time theory [Hansen & Pachl, 2014].
Decision variables (2)

- Alternative departure times

\[ x_b \]
\[ x_{b2} \]
Decision variables (3)

- Alternative speed profiles

![Graph showing alternative speed profiles with time on the x-axis and speed on the y-axis, labeled with $x_{b3}$ and 60.]

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Decision variables (4)

- Alternative paths

\[ x_{b4} \]
Constraints (1)

- Uniqueness [Caimi 2009, Fuchsberger 2012]

\[
\begin{align*}
\sum_{b \in B_{t,1}} x_b &\leq 1 \quad \forall t \in \mathcal{T} | s_0 \text{ is no portal} \\
\sum_{b \in B_{t,1}} x_b &\geq 1 \quad \forall t \in \mathcal{T} | s_0 \text{ is a portal}
\end{align*}
\]
Constraints (2)

- Avoid conflicts [Caimi 2009, Fuchsberger 2012]

\[ \sum_{b \in C} x_b \leq 1 \quad \forall C \in C', P \in R \setminus \bigcup_{s \in S} P_s \]
Objectives

- Minimize train delays
- Minimize customers’ inconvenience
- Energy efficiency
Information flows (1)

- Variables generation via simulations

Generator

- Extract information
- Routing, stopping pattern, speed profile, …

Database

Blocking Time Stairways + energy consumption

Simulator
Information flows (2)

- Rescheduling using off-line Blocking time stairways database
Modelling energy consumption

- How to introduce information about the tractive energy required by the different trains in the Resource Conflict Graph?
- Is energy efficiency a constraint or an objective?
Resource Conflict Graph
– introducing energy efficiency as an objective

**Multi Objective Func**

\[
\min f(x) = w_1 f_1(x) + w_2 f_2(x)
\]

**Targets**

- Minimize the overall arrival delay at stations

\[
f_1(x) = \sum_{z \in Z, s \in S_z} W_{z,s} \sum_{T \in T_z} x_T (t_{T,s} - \hat{t}_{s,z})
\]

- Minimize the energy consumption

\[
f_2(x) = \sum_{z \in Z} \sum_{T \in T_z} E_T x_T
\]

**Constraints**

\[
\sum_{T \in T_z} x_T \leq 1 \quad \forall z \in Z
\]

\[
\sum_{T \in \bigcup_{z \in Z} T_z | T \rightarrow T'} x_T \leq 1 \quad \forall T \in \bigcup_{z \in Z} T_z, \forall r
\]

\[
x_T \in \{0, 1\} \quad \forall T \in \bigcup_{z \in Z} T_z
\]


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First experiences

Case study developed on the characteristics of the EBL physical model.
Some results

Current scenario
Some results

Optimized scenario

![Optimized scenario chart]

- **Initial scenario**
  - Overall delay (min): 9.73
  - Total energy consumption (MJ x 1000): 14.37
  - Computation time (s*10): 0

- **RT1**
  - Overall delay (min): 8.5
  - Total energy consumption (MJ x 1000): 13.17
  - Computation time (s*10): 5.1

- **RT1 + optimal speed profiles**
  - Overall delay (min): 7.85
  - Total energy consumption (MJ x 1000): 10.51
  - Computation time (s*10): 16.4
Resource Conflict Graph
– introducing energy efficiency as a constraint

- Energy targets as constraints
  - The main objective remains the minimization of delays
- Bound energy consumption in each rescheduling horizon via

\[ \sum_{b} E_b x_b \leq \epsilon_{E,\text{max}} \]
Infras...
**Schedule**

- Official yearly timetable: 7 – 8 a.m.
- Artificially prolonged stop (rescheduling).
- Mixed traffic*: passenger (regional and long-distance) and freight.

* Feature not exploited in this work
Results with different $\epsilon$

11.7% saving without additional delays
An outlook to future requirements: Dynamic capacity optimization
A gentle reminder…

The primary goal of a transport system is to provide a reliable and satisfying service for moving people and goods

Increasing traffic means increasing capacity utilization of infrastructures
Do we have capacity residuals to use?

A more energy efficient transport system may not be interesting for users… maybe eco-friendly sounds more appealing.
Capacity as such does not exist. Railway infrastructure capacity depends on the way it is utilized. (UIC 406)
Concept of Dynamic capacity optimization:

ADapted schedules and train trajectories + Highly ACcurate production

towards fully automated train operation

The ADAC principle
Dynamic Capacity Optimization is based on **real time adapted** schedules and **accurate** operation.

This leads to **full automation** of the entire railway system.

Automation can provide **15 to 25 % more capacity** in station areas.

**Capacity extentions** in station areas affects positively the capacity of the **entire network**.

Capacity extention with DCO does not require additional infrastructures, so it can be applied **earlier**, with **less investments** and with a **reduced energy footprint**.
Five technical elements of Dynamic Capacity Optimization

1. **Real-time rescheduling:** Adapt the timetable in real-time according to the current traffic situation

2. **Speed profile optimization:** Generate speed profiles for the train in order to avoid unplanned stops

3. **Integrated control loops:** Link continuously rescheduling and train driving

4. **Automatic Train Operation:** Ensure the precise application of the newly defined trajectories

5. **Optimized time-reserve distribution:** Allocate recovery and buffer times on not capacity-critical sections
Focuses and key words:

- **Energy efficiency strategies** can be applied in railway operation, but two level have to be considered together (train driving and traffic control)

- Railway system is a **complex system**, made of subsystems. This means **integrated solutions**

- **Real data** are essential for research and development of solutions (Big Data issue is coming…)

- **Small extra-time availabilities** can impact significantly on energy consumption

- **Simulation** gives both a global view of the rail traffic when energy efficient strategies are implemented and a zoom to single trains

**Conclusion**

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Primitive solution  →  Complex solution  →  Simple solution

We are (still) here
Focuses and key words:

- **Automation** can increase the adherence between planned and realised (automatic timetabling, automatic rescheduling, automatic train operation)
- **Freight trains** should use specific models and technologies, to consider the inner variabilities of their operation

“It is the sum that makes the total” – Toto’ (actor, writer, songwriter, poet)
Antonio Griffo Foci Flavio Angelo Ducas Comneno Porfiro-genito Gagliardi de Curtis di Bisanzio
Conclusion

For the use of simulation-based approaches

Simulation is a very powerful tool:

• Surrounding conditions that can affect/be affected by modification of control variables are included.
• Current technologies, such as parallel computing, allow quick responses.
• There is a variety of models to consider in dependance of the problem scale (micro, meso, macro).

But we have to consider carefully the following:

• Monitoring phase for data acquisition gives definitive feedback about the entity of energy consumed in normal condition and in energy efficiency condition
• Monitoring data are fundamental for models calibration. Without calibration, it is better to play videogames.

“God takes care of us, all others have to provide data!” (cit.?)
Thank you for your attention!
Q&A