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

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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

- 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.

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

Technology, and a better use of it
General considerations

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)

Number of trains per route and day spent on rail network (source: UIC 2014)

<table>
<thead>
<tr>
<th>Country</th>
<th>Passenger trains</th>
<th>Freight trains</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>39</td>
<td>8</td>
</tr>
<tr>
<td>Russia</td>
<td>16</td>
<td>33</td>
</tr>
<tr>
<td>Italy</td>
<td>47</td>
<td>7</td>
</tr>
<tr>
<td>China</td>
<td>32</td>
<td>44</td>
</tr>
<tr>
<td>Austria</td>
<td>57</td>
<td>25</td>
</tr>
<tr>
<td>Germany</td>
<td>64</td>
<td>20</td>
</tr>
<tr>
<td>UK</td>
<td>89</td>
<td>7</td>
</tr>
<tr>
<td>Japan</td>
<td>98</td>
<td>9</td>
</tr>
<tr>
<td>Netherlands</td>
<td>122</td>
<td>10</td>
</tr>
<tr>
<td>Switzerland</td>
<td>128</td>
<td>27</td>
</tr>
</tbody>
</table>
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

Planning

Real time

Energy supply management

Rail traffic management

Train operation
**Passenger trains vs Freight trains**

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

**VS**

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

Predefined models and operating conditions

More subjected to rescheduling

Predefined models may be unrealistic

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>planning</strong></td>
<td><strong>operation</strong></td>
<td><strong>planning</strong></td>
<td><strong>operation</strong></td>
</tr>
</tbody>
</table>
| **Single train control** | • Departure time (Green wave)  
  • Efficient paths (short, flat,...)  
  • Energy efficient Timetabling  
  • ... | • Anticipating train control for unplanned stops avoidance  
  • Rescheduling for conflict avoidance  
  • ... | • Departure and arrival  
  Synchronization (optimal use of storage systems at wayside)  
  • ... | • Departure and arrival  
  scheduling  
  • Use of energy storage systems for power peaks control  
  • ... |
|               | • Energy optimal speed profile parameters  
  • Coasting phase introduction  
  • Aerodynamics  
  • ... | • Energy optimal speed profile adoption and/or modification (ADL)  
  • ... | • Energy optimal speed profile parameters  
  • ... | • Energy optimal speed profile parameters (minimization of acceleration phases)  
  • ... | • Rescheduling during low traffic hours  
  • Intentional stops  
  • ... |

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... and our expertise at IVT- ETH

**Tractive Energy Consumption Reduction**

- Scheduling → PhD. Gabrio Caimi
- Rescheduling → Ambra Toletti and Valerio De Martinis
- Anticipating train control → PhD. Xiaolu Rao
- Speed profile optimization → Valerio De Martinis

**Analysis of Energy Consumption components**

- Weather conditions → Axel Bomhauer-Beins
- Interaction with the public grid → 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.
Modeling the system

What do we need

How can we implement energy efficiency? First we need time availabilities …

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?
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

station A  |  station B  |  station C

- Scheduled running time
- Minimum running time
- Blocking time

RTR  Running Time Reserve
DTR  Dwell Time Reserve
B\textsubscript{t}  Buffer Time
Modeling the system
Speed profiles and trajectories

Planning:
energy efficient speed profiles

Real time operation:
speed profiles information (to drivers)

Energy efficient timetables

Real time operation:
Trains position information (to dispatchers)
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

- **Exogenous scenario variables**
- **Control variables**
  - Cruising speeds (according to variation of speed limits)
- **Targets and Constraints**
  - 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

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

- **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

- Input:
  - Rolling stock
  - Infrastructure
  - Timetable

- Simulation:
  - Interactivity / Disturbances
  - Animation

- Output:
  - Diagrams
  - Train graphs
  - Occupations
  - Statistics

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>
</tr>
</thead>
<tbody>
<tr>
<td>ZHB - ZSTH</td>
<td>1.745</td>
</tr>
<tr>
<td>ZSTH - STET</td>
<td>5.351</td>
</tr>
<tr>
<td>STET - DUE</td>
<td>2.659</td>
</tr>
<tr>
<td>DUE - SCWE</td>
<td>3.279</td>
</tr>
<tr>
<td>SCWE - NAEN</td>
<td>2.685</td>
</tr>
<tr>
<td>NAEN - UST</td>
<td>2.679</td>
</tr>
</tbody>
</table>

SBB-CFF-FFS Re 450

**Type and origin**
- Power type: Electric
- Builder: SLM, ABB, SIG

**Specifications**
- **UIC classification**: Bo’Bo’
- **Gauge**: 1,435 mm (4 ft 8 1⁄2 in)
- **Length**: 18,400 mm (60 ft 4 in)
- **Locomotive weight**: 74 tonnes (72.8 long tons; 81.6 short tons)
- **Electric system(s)**: 15 kV 16 2⁄3 Hz AC Catenary
- **Current collection method**: Pantograph

**Performance figures**
- **Maximum speed**: 130 km/h (81 mph)

**Career**
- **Operator(s)**: Swiss Federal Railways
- **Number(s)**: Re 450 000 – Re 450 114
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>
</tr>
</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>
</tr>
<tr>
<td></td>
<td>Energy Optimal</td>
<td>97.864</td>
<td>0.731</td>
<td>2.168</td>
</tr>
<tr>
<td>NAEN - UST</td>
<td>Time Optimal</td>
<td>117</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy Optimal</td>
<td>86.254</td>
<td>0.524</td>
<td>1.955</td>
</tr>
</tbody>
</table>
Some results from first implementation

- Time optimal
- Energy saving

-16.7%
Some results from first implementation
An example on freight trains

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

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

• An outlook to future requirements: Dynamic capacity optimization

• Conclusion and further perspectives
Overview of rescheduling models

FlexiblePath AG
AlternativeGraph

RCG
Retiming
FlowConservation
Reformulated
FixedArcs
FP
Trajectories
Reordering
Rerouting

SimultaneousRescheduling&Rerouting
BlockingTimeStairways
ConflictCliquen

ResourceConflictGraph
AlternativeArcs
Microscopic

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
Current solutions

Energy efficient scheduling through the RCG approach

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

Multi objective rescheduling through the RCG approach
Decision variables (1)

- Based on the blocking time theory [Hansen & Pachl, 2014].

\[ x_b \]
Decision variables (2)

- Alternative departure times
Decision variables (3)

- Alternative speed profiles

\[ \text{time} \]

\[ x_{b3} \]
Decision variables (4)

- Alternative paths

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

- Uniqueness [Caimi 2009, Fuchsberger 2012]
Constraints (2)

- Avoid conflicts [Caimi 2009, Fuchsberger 2012]
Objectives

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

- Variables generation via simulations

Generator

- Extract information
- Routing, stopping pattern, speed profile, …
- Blocking Time Stairways + energy consumption

Database

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

- Minimize the energy consumption
  \[
f_2(x) = \sum_{z \in Z} \sum_{T \in T_z} E_T x_T
\]

**Constraints**

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

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

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

First experiences

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

Current scenario
Some results

Optimized scenario

<table>
<thead>
<tr>
<th>Testadt</th>
<th>Ypsikon</th>
<th>Zetthausen</th>
<th>Pewald</th>
<th>Utal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rescheduling point</td>
<td>08:00</td>
<td>08:20</td>
<td>08:30</td>
<td>08:40</td>
</tr>
</tbody>
</table>

- **Overall delay (min)**
- **Computation time (s*10)**
- **Total energy consumption (MJ x 1000)**

Initial scenario:
- Overall delay: 9.73 min
- Computation time: 5.1 s
- Total energy consumption: 7.85 MJ x 1000

RT1:
- Overall delay: 14.37 min
- Computation time: 8.5 s
- Total energy consumption: 13.17 MJ x 1000

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

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

\[ \sum_b E_b x_b \leq e_{E,\text{max}} \]
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 in railway

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 ACurate 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 extensions in station areas affects positively the capacity of the entire network.

Capacity extension 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
Conclusions
Conclusion

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

Primitive solution → Complex solution → Simple solution

We are (still) here
Conclusion

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 Focas 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!