Towards the automation of train operation and traffic management: modeling and optimization aspects

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Agenda

From the «planet» of automation in transportation …

… to modeling and optimization of a specific sub-problem …

… back to impact for the whole transportation system.
Motivating automation in transportation ...
Forecast of population growth in Switzerland until 2040

+ 20%
Demand in public transport services growth until 2040

Source: Verkehrsperspektiven 2040, Bundesamt für Raumentwicklung ARE, 2016
Costs of transport from public authorities in Switzerland

8.5 billions CHF in 2015  
Trend increasing for the coming years (new infrastructure, denser timetable, …)

Many other countries have similar or higher public costs for transportation

Source: eidgenössische Finanzverwaltung, 2015
Motivating challenges in railway operations

<table>
<thead>
<tr>
<th>Improvement of QUALITY</th>
<th>Reduction of COSTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>➔ More capacity</td>
<td>➔ Many countries face financial difficulties and have to reduce their expenses</td>
</tr>
<tr>
<td>➔ Fully integration for a door-to-door offer (complete transport service)</td>
<td>➔ Focus on cost reduction</td>
</tr>
<tr>
<td>➔ At least same reliability</td>
<td></td>
</tr>
<tr>
<td>➔ At least same safety</td>
<td></td>
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→ Higher costs?  
→ Reduction of quality?

Contradiction? Conflict in the objective?  
Or need or structural change in the approach?
Facing both challenges simultaneously: Automation of transport systems!

Is the automation of transport operation the approach to follow?

→ This leads to:

- Improvement of capacity (less tolerance needed)
- Improvement of reliability (more precision in driving, optimized rescheduling, better forecast)
- Better customer information and easier integration with other transport means (live information)
- Same or higher safety (human errors will be removed)

and

- Reduced costs (much less manual work)
What’s automatic operation and traffic management?

→ A transport system consists of three essential elements:
  ▪ Infrastructure
  ▪ Vehicles (Trains, trams, buses)
  ▪ Operating rules and procedures
Situation in subway systems

Kobe New Transit
(1st fully automated system, 1981)

Lausanne, M2

Paris, M1
Transition with mixed service

Copenhagen, lines 1 and 2
Why just not apply the subways-methods to railways?

➔ The matter is not the railway as non-underground or long distance transport, the matter is primarily the longer and integrated history:

- **Infrastructure**
  - old infrastructure
  - no remote control possible

- **Modeling & algorithms**
  - Complex network
  - (optimization needed)

- **Organization & regulation**
  - open access
  - (international traffic, many companies)

- More external influences
  - (e.g. level crossing)

- Difficult train dynamics
Current state in railway systems?

- Huge energy on the topic, many products on the market (or own development of railway companies) for subquestions such:
  - Speed advisory for driver
  - Local optimization, decision support systems
  - Crew and rolling stock planning, …

Frittered in specific solutions and approaches

Not known approaches on fully automation implemented or in realization

- Standardization as a chance to align research and market solutions and enable a fair competition (use of ERTMS?)
1. Automation of one loop can go independently from the other.

2. The better and reliable the one loop works, the easier is for the other loop to work.
   This dependency is even quite strong, simultaneous consideration of both loops yields relevant results*.

3. The localization and information system only affect the quality of data preparation. Separation of modules “data preparation” and “rescheduling” enables a general method, applicable also with different localization technologies, and can be standardized.

* X. Rao, Holistic rail network operation by integration of train automation and traffic management, ETH Zurich, 2015
Via modeling of the traffic management problem ...
Focus and zoom

- Let now focus, step by step, on a specific subproblem
- Deepdive on optimization based on Operations Research methods

- Focus on
  - Outer loop (Traffic management)
  - Rescheduling module
  - Optimal rescheduling in a main station area

- Important reminder (Statement 3): method independent of current state of inner loop, localization technique or safety system (but with impact on quality)
Basic idea:
Consider a longer time horizon for an efficient solution but definitely fix only the minimum necessary.

Model predictive control approach

Past

Very next future (already fixed)

Next future (to be fixed)

Further future (to consider, not to be fixed yet)

Current time

Earliest time a decision can be executed

Next computation step

time
Goal of rescheduling

What’s the goal (objective function) of rescheduling?

<table>
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<tr>
<th>Option</th>
<th>Description</th>
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<tr>
<td>a. Going back as quick as possible to the original production plan?</td>
<td>NO, otherwise you will explicitly delete connections or trains (very bad quality in the short term)</td>
</tr>
<tr>
<td>b. Minimize the delay for the customer?</td>
<td>YES and NO, (final) delay is very important, but not only service. How about cancellation of trains? Non-linear perception of delay.</td>
</tr>
<tr>
<td>c. Best possible fulfillment of the service (intention)?</td>
<td>YES, passenger will receive their service for the transport for A to B. But attention, this means: definition, measure, robust, information.</td>
</tr>
</tbody>
</table>
Degree of freedom of rescheduling

Which are the possible degree of freedom for rescheduling?

- Rerouting through other lines
- Rerouting in nodes
- Change speed profile and/or passing times
- Break/wait connection
- Additional train stop
- Cancel or add trains
- ...
Boundary conditions

What are the boundary conditions to consider for reschedule?

- Properties of rolling stock and infrastructure (physics and safety)
- Service intention (published timetable, online situation)
- Situation now and after computation time (based on measured data AND prediction/assumptions)
- Time allowed for change (technical and commercial)
- Quality of communication of the decision (signalling, DMI, …)
- …
Through a two-level strategy for solving the problem …
Two level of details

Macro timetabling:
- Simplified information
- Enables overview on whole network and focus on key factors

Micro scheduling:
- Detailed information
- Focus on local zone for creation of a conflict-free schedule
Micro scheduling: Network decomposition

Condenstation vs. Compensation zones

Condensation zone (main station area):
- Bottleneck
- Maximum speed
- Time discretization
- Exploit routing

Compensation zone:
- Add time reserves
- Few routes
- Exploit train dynamics (speed profiles)

Ports
- Coordination of zones
To optimization of a specific sub-problem …
Micro scheduling in condensation zone

Resource Conflict Graph model (RCG)
- Generates conflict-free train schedule
- Exact method (ILP based)
- Enables feedback in case of infeasibility
- Strong LP-relaxation
- Fast CPU time also for large instances
Conflict graph model: example

Find *Stable Set*, one node for each color / train

Conflict graph: example
Conflict graph – ILP formulation

\( x_{ij} \in \{0, 1\} \) indicate whether node \( v_{ij} \) is in the set or not

Find

\[
\begin{align*}
\sum_{j=1}^{m_i} x_{ij} &= 1 & \forall i = 1, \ldots, n \\
x_{ij} + x_{kl} &\leq 1 & \forall \text{edges } (v_{ij}, v_{kl}), i \neq k \\
x_{ij} &\in \{0, 1\}
\end{align*}
\]
Conflict graph – solving problems

→ Commercial ILP solver (CPLEX) takes too much time for large problem instances, even for improved clique inequalities\(^1,2\).

→ The heuristic attempt (Sequential fixing\(^1\), Randomized FPI\(^3\)) is faster, but fails for some (large) instances.

\(^1\) Zwaneveld et al. 1996
\(^2\) Caprara et al. 2007
\(^3\) Fixed Point Iteration, Herrmann et al. 2005
Conflict graph: improved formulation

Replace the 6 constraints of the form

\[ x_{ij} + x_{kl} \leq 1 \]

with the clique constraint (cut)

\[ x_{11} + x_{23} + x_{34} + x_{41} \leq 1 \]
Detection of cliques in conflict graph

- Finding all cliques in a graph is NP-hard
  - Even finding only the maximum clique is NP-hard
- Reducing size by eliminating dominated nodes is quite time consuming (Zwaneveld et al. 2001)
- Reducing size by considering a subset of routes leads to suboptimal solutions
- Structure of the problem should be better exploited
Basic idea: include topology

Conflict Graph:

1 Conflict

6 Conflicts
Conflict modeling for a resource

- Time Interval where the Resource is occupied by a train
- Conflicts between two trains
- Grouped conflicts between several trains = „Cliques“

→ Easy algorithm, strong theoretical and practical properties

<table>
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<th>Scenario</th>
<th>Conflict constraints</th>
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<tbody>
<tr>
<td>Lucerne</td>
<td>grouped 2000 28 000</td>
</tr>
<tr>
<td>Berne</td>
<td>pairs 10 000 10 Mio</td>
</tr>
</tbody>
</table>
RCG – ILP formulation

\( x_{ij} \in \{0, 1\} \) indicate whether node \( v_{ij} \) is in the set or not

Find \( x_{ij} \)

\[
\begin{align*}
\text{s.t.} \quad & \sum_{j=1}^{m_i} x_{ij} = 1 \quad \forall i = 1, \ldots, n \\
\end{align*}
\]

- \( \sum_{(i,u)\in I} x_{iu} \leq 1 \quad \forall I \in F_k, \quad \forall \text{ resources } k \)

- \( x_{ij} \in \{0, 1\} \)

where \( F_k \) is the Familiy of Sets corresponding to interference cliques.
Test case: Berne

- Radius of about 10 km, 600 switches, 300 signals
- Simulation of a complete day with real data (1500 trains)
- Per instance 32’000 variables, 54’000 constraints
- Few seconds per (optimal) solution, very rarely over 6 seconds
- For a first feasible solution it takes significantly less

*Tests from G. Caimi and M. Fuchsberger, ETH Zurich, 2009-2012*
Strengths of the approach

- Explicit consideration of the service intention: customers needs are in focus
- Macro level: Global network overview
- Micro level: new stronger conflict modeling
  - Considering details (practical validation)
  - Independent consideration of the main station area
  - Alternative solution if infeasible
Back to implementation in practice …
Way to automation – Transition 1/2

Fully automated

Conventional
Way to automation – Transition 2/2

Mixed system
(automatic and conventional)

Automatic rescheduling only in certain regions or as a decision support system

Mixed traffic of trains with and without train driver
Way to automation - Transition

- Fully automated
  - Technical easier
  - Offer restricted

- Mixed system
  - Technical limited
  - Offer not restricted

Essential element for practicability
Transition is essential element of the approach
Way to automation – recent changes at SBB

Classic train control

Adaptive train control (ADL)
Hub optimization technology (HOT)
Way to automation – human and political aspects

→ Change management ist not to neglect

→ Perception of safety (with automatic train operation) and security (without staff on train) is to deepen and take into account
… and its impact for the whole planning process.
Impact of automatic rescheduling for the whole planning process

Customer demand

Service intention

Timetable

- Less tolerance
- Other distribution of time reserves
- Flexible timetable

Adapted production plan (Rescheduling)

Adjust infrastructure and resources

Simulation
Other infrastructure
Less redundancy
Outlook
Outlook

(Much) work at all levels is still needed

- **Optimization**: Rescheduling of complex networks in real-time
- **Architecture**: Standardization (via ERTMS?)
- **Technology**: for better communication, localization, and reduced costs of the needed assets
- **Planning**: Use of future operations systems also in planning and construction phase
- **Regulative** questions
- **Human**: acceptance, transition, security
- **Scope**: Advanced optimization vs. full integration of all transport systems (much more complex, no more closed system)
- **Vision**: Automated traffic management of a network of autonomous vehicles
Questions?
Thank you very much for your attention!