Towards operationally feasible railway timetables

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Outline

1. Introduction
2. Problem description
3. Methodology
4. Experimental results
5. Conclusions
Current state in railway traffic

- Constant growth of demand for passenger and freight railway transport
- Heavily congested networks
- Reaching maximum available infrastructure capacity
- Experiencing delays
Current state in railway traffic

- Constant growth of demand for passenger and freight railway transport
- Heavily congested networks
- Reaching maximum available infrastructure capacity
- Experiencing delays

Existing need for better planning to satisfy a high level of service (ERA, UIC, IMs, RUs...)

N.Besinovic (n.besinovic@tudelft.nl)
Timetable planning

**INPUT:**
- Train line requests (OD, stops, frequencies, rolling stock)
- Track topology
- Rolling stock with dynamic characteristics
- Passenger connections and rolling stock turn-arounds

**OUTPUT:**
- Timetable: arrival, departure and passing times at timetable points

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Goals:

- **Efficiency** - short travel times and seamless connections
- **Realizability** - scheduled RT > minimum RT
- **(Operational) Feasibility** - no conflicts
- **Stability** - acceptable capacity occupation in corridors and stations
- **Robustness** - cope with system stochasticity
Timetable planning

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**Operationally feasible timetable**

An operationally feasible timetable has no conflicts on the microscopic level (block and track detection sections) between train’s blocking times.
Time-distance diagram
How to guarantee the operational feasibility in timetabling models?

Blocking time diagram for the train series 3501
Blocking time diagram

Question:

□ How to guarantee the operational feasibility in timetabling models?
Minimum headway time (Hansen and Pachl, 2014)

A minimum headway time is the time separation between two trains at certain positions that enable conflict-free operation of trains.
Minimum headway time

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Minimum headway time $L_{ij}$ depends on:

- infrastructure characteristics: block lengths
- signalling system
- train engine characteristics
- (scheduled) train running times
Minimum headway time

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A minimum headway time is the time separation between two trains at certain positions that enable conflict-free operation of trains.

Minimum headway time $L_{ij}$ depends on:

- infrastructure characteristics: block lengths
- signalling system
- train engine characteristics
- (scheduled) train running times
- not a single value
State-of-the-art

So far:

- Efficiency ☑
- Realizability ☑
- (Operational) Feasibility ☹
- Stability - ☑ ☹
- Robustness - ☑
Periodic event scheduling problem (PESP)

Serafini & Ukovich (1989)
Periodic timetable with cycle time $T$
Periodic events: arrival & departure times $\pi_i \in [0, T)$
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Constraints:

$$lowerBound_{ij} \leq \pi_j - \pi_i + z_{ij} T \leq upperBound_{ij}$$
Periodic event scheduling problem (PESP)

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Periodic timetable with cycle time $T$
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\[
\text{lowerBound}_{ij} \leq \pi_j - \pi_i + z_{ij}T \leq \text{upperBound}_{ij}
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Period shift: $z_{ij}$ - define the order of trains
Serafini & Ukovich (1989)

Periodic timetable with cycle time $T$

Periodic events: arrival & departure times $\pi_i \in [0, T)$

Constraints:

$$\text{lowerBound}_{ij} \leq \pi_j - \pi_i + z_{ij} T \leq \text{upperBound}_{ij}$$

Period shift: $z_{ij}$ - define the order of trains
Solving PESP

\[ (PESP - N) \quad \text{Min} \quad f(\pi, z) \]

such that

\[
\begin{align*}
l_{ij} & \leq \pi_j - \pi_i + z_{ij} T \leq u_{ij} \\
0 & \leq \pi_i < T, \quad \forall i \\
z_{ij} & \text{ binary}
\end{align*}
\]

\[ \forall (i, j) \in A \]
Computing operationally feasible timetables

Solving PESP-N:

- Fixed minimum headways
- Can be violated when scheduled running time increases
Computing operationally feasible timetables

Solving PESP-N:
- Fixed minimum headways
- Can be violated when scheduled running time increases

How to include microscopic details in timetable planning models?
- Iterative approach
- Integrated approach

Micro model (*Comp-aided Civil and Inf. Eng., 2016*):
- √ Compute operational train speed profiles
- √ Conflict detection
- √ Update headways
Integrated approach

Can we add microscopic details directly to the macroscopic level?
Integrated approach

Can we add microscopic details directly to the macroscopic level? Yes.
Integrated approach

Can we add microscopic details directly to the macroscopic level? Yes.

Introduce **flexible minimum headways** in PESP
Integrated approach

\[(PESP - N) \text{ Min } f(\pi, z)\]

such that

\[l_{ij} \leq \pi_j - \pi_i + z_{ij} \cdot T \leq u_{ij} \quad \forall (i, j) \in A\]

\[0 \leq \pi_i < T, \quad \forall i\]

\[z_{ij} \text{ binary}\]
Integrated approach

\[(PESP − FlexHeadways) \quad \text{Min} \ f(\pi, z)\]

such that

\[
\begin{align*}
    l_{ij} &\leq \pi_j - \pi_i + z_{ij} \cdot T \leq u_{ij} \\
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    0 &\leq \pi_i < T, \quad \forall i \\
    z_{ij} &\text{ binary}
\end{align*}
\]

\[L_{ij} = F(\text{running times of two trains})\]
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For each train pair at each timetable point:

- vary running speeds = amount of time supplements
- compute minimum headway time for each trains-speeds variations
- get functional relationship between given time supplements and minimum headways $\rightarrow L_{ij}$
\[ L_{ij} = F(\text{running times of two trains}) \]

For each train pair at each timetable point:

- \( \Box \) vary running speeds = amount of time supplements
- \( \Box \) compute minimum headway time for each trains-speeds variations
- \( \Box \) get functional relationship between given time supplements and minimum headways \( \rightarrow L_{ij} \)

Expected: bigger speed difference \( \rightarrow \) bigger minimum headway time
- \( \Box \) more homogenized running times \( \rightarrow \) smaller minimum headway time
- \( \Box \) second train faster \( \rightarrow \) minimum headway increases
\[ L_{ij} = F(\text{running times of two trains}) \]

- \( \text{run}_{ik} \) - running time supplement of the first train (in %)
- \( \text{run}_{jl} \) - running time supplement of the second train (in %)
- \( R_{ij} \) - relative difference between time supplements of two trains (in %)

\[ R_{ij} = \text{run}_{ik} - \text{run}_{jl} \]
\[ L_{ij} = F(\text{running times of two trains}) \]

\[ \text{run}_{ik} - \text{running time supplement of the first train (in \%)} \]

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\[ R_{ij} - \text{relative difference between time supplements of two trains (in \%)} \]

\[ R_{ij} = \text{run}_{ik} - \text{run}_{jl} \]

\[ \text{run}_{ik} = r_{ik}/\bar{r}_{ik} - 1 \]

\[ \text{run}_{jl} = r_{jl}/\bar{r}_{jl} - 1 \]
\[ L_{ij} = F(\text{running times of two trains}) \]

Headway relation for train lines 6001 and 16001 at station CI

\[ \text{Minimum headway time } L_{ij} \text{ [s]} \]

\[ \text{Running time difference } \text{run}_i - \text{run}_j \text{ [s]} \]

\[ \text{run}_i - \text{run}_j > 0: \text{ the first train is faster}^* \]
\[ \text{run}_i - \text{run}_j < 0: \text{ the second train is faster}^* \]

* Assuming the same category trains
\[ L_{ij} = F(\text{running times of two trains}) \]

**Headway relation for train lines 6001 and 16001 at station CI**

- \( \text{run}_1 - \text{run}_2 > 0 \): the first train is faster*
- \( \text{run}_1 - \text{run}_2 < 0 \): the second train is faster*

* Assuming the same category trains
Linear dependency between \( \text{run}_{ik} \) and \( \text{run}_{jl} \)

\[
L_{ij} = \alpha_{ij} \cdot R_{ij} + l_0
\]

\( \alpha_{ij} \) - slope of \( L_{ij} \)

\( R_{ij} \) - relative difference between time supplements of two trains (in %)

\( l_0 \) - minimum headway time for \( \text{run}_{ik} = \text{run}_{jl} \)
Integrated approach

\[
(PESP - \text{FlexHeadways}) \quad \text{Min } f(\pi, z)
\]

such that

\[
\begin{align*}
I_{ij} & \leq \pi_j - \pi_i + z_{ij} \cdot T \leq u_{ij} \\
\alpha_{ij} \cdot R_{ij} + l_0 & \leq \pi_j - \pi_i + z_{ij} \cdot T \leq u_{ij} \\
R_{ij} & = \text{run}_{ik} - \text{run}_{jl} \\
0 & \leq \pi_i < T, \quad \forall i \\
z_{ij} & \text{ binary}
\end{align*}
\]

\[
\forall (i, j) \in A_{\text{run}} \cup A_{\text{dwell}} \\
\forall (i, j) \in A_{\text{headway}}
\]

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Feasible timetabling

November 17, 2016 21 / 31
Case studies

Case network: Utrecht - Eindhoven network (two intersecting corridors)

- 15 stations and junctions
- 40 trains/h
- 96 events and 148 activities

Minimum running time supplement: 5%
Maximum running time supplement: 20%
Minimum dwell times: 60-120 s

Test: Iterative micro-macro and integrated PESP-FlexHeadway models
Case 1: Utrecht-Eindhoven network

Figure: Line plan
Table: Solutions obtained after the first iteration

<table>
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*After first iteration
# Computed timetables

**Table:** Solutions obtained after the first iteration

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Iterative micro-macro framework finished after 10 iterations
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*After first iteration

Iterative micro-macro framework finished after 10 iterations
PESP-FlexHeadway allocated more time supplements to satisfy new headways
Computed timetables

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*After first iteration
Iterative micro-macro framework finished after 10 iterations
PESP-FlexHeadway allocated more time supplements to satisfy new headways
CPU times are comparable
Iterative micro-macro framework

Time distance diagram for corridor Ut–Ehv

Distance [stations]

Time [min]

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Feasible timetabling

November 17, 2016
Iterative micro-macro framework
Integrated framework: PESP-FlexHeadway
Integrated framework: PESP-FlexHeadway
Some more headways...

Headway relation for train lines 3501 and 801 at station Htn

Headway relation for train lines 800 and 3500 at station Btl

Headway relation for train lines 800 and 6000 at station Htn
**Conclusions**

Main observations:

- We *can* compute operationally feasible timetables
- Iterative approach solves within a *limited number of iterations*
- Minimum headway times as a *function of running times*
- Macroscopic **Flexible minimum headway model** formulation generates (almost) operationally feasible solutions
Conclusions

Main observations:

☐ We can compute operationally feasible timetables
☐ Iterative approach solves within a limited number of iterations
☐ Minimum headway times as a function of running times
☐ Macroscopic **Flexible minimum headway model** formulation generates (almost) operationally feasible solutions

Pursuing the (passenger) happiness

☐ Is linear approximation always good? Piecewise linear?
☐ Include stability and robustness in the objective function
☐ Test the model on bigger instances
Thank you for your attention
Iterative micro-macro framework

Figure: Micro-macro iterations