Micro-simulation based analysis of railway lines robustness

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A method to benchmark investments

Infrastructure modifications
- Alignment
- Signaling

Rolling stock modifications
- Acceleration
- Max. Speed
- Braking performance

Sets of rules
- Min. Headway
- Time Supplements
Approach
Sensitivity to primary delays and traffic volume

**Sensitivity to primary delays**

- Primary delays deterministic generation (1,...,n)
- Synthetic indices to describe the measurements

**Traffic volume increases**

- Test timetables generated from a reference timetable up to the maximum capacity consumption

**Micro-simulation**

- Running time calculation
- Trains interaction
- Delays measurement

**Skimming method**

- Reduce the number of simulation runs through the selection of a set of representative trains
Measurements

**Line exploitation**
- Capacity consumption (UIC 406)

**Measure and description of primary delay effects on the line**
- Total delay
- Settling time (Recovery time)

**Individual impact on trains**
- Share of trains delayed
- Average delay per train
Total delay

Sum of each train’s delay at every timing point

Regression to square parabolas

Index: Regressed parabola
Second derivative

Regression to square parabolas

Index: Regressed parabola
Second derivative

\[ y = 13,97x^2 - 27,848x - 14,067 \]
\[ R^2 = 0,9907 \]

\[ y = 14,864x^2 - 40,542x + 9,5333 \]
\[ R^2 = 0,9959 \]

\[ y = 23,72x^2 - 87,183x + 71,3 \]
\[ R^2 = 0,9969 \]

\[ y = 32,144x^2 - 140,49x + 133,23 \]
\[ R^2 = 0,9962 \]

\[ y = 47,258x^2 - 172x + 119,2 \]
\[ R^2 = 0,9578 \]

Primary delay [min]

Total delay [s]

0 500 1000 1500 2000 2500 3000 3500
1 2 3 4 5 6 7 8 9 10

A (11 trains/h) B (12 trains/h) C (14 trains/h)
D (16 trains/h) E (18 trains/h)
Settling time (Recovery time)

- Lapse of time until all the trains are on time
- Irregular shape: basic timetable as a reference
- Minimum Mean Squared Error
- Index: Amplification factor
- Applicable also to the Number of trains involved

![Diagram showing SETTLING TIME vs PRIMARY DELAY for different timetables: Timetable “a”, Timetable “d”, Scaled timetable “a”](image)
Average delay per train

\[ y = 36,84x - 103,67 \]

\[ R^2 = 0,9255 \]
The skimming method

7:00 – 8:00 Timetable

IC (NS Hispeed)  Sprinter
Intercity  Stoprein
Sneltrein
The skimming method

**7:00 – 8:00 Timetable**

Same amount of primary delay

Different impact

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10 DTU Transport, Technical University of Denmark
The skimming method

Thorough Simulation
- Primary delay to each train

System behavior
- Total delay for each simulation
- Average total delay

Subset selection
- Mean Squared Error
- Most representative subset

![Chart showing total delay at [s] vs primary delay [min] for 1902 and average cases.](chart.png)
The skimming method

Load reduction

- Total number of simulations
  \[ n_{si} = n \cdot \sum_{j=1}^{n_{tt}} v_j \cdot n_{sc} \]

- Skimmed number of simulation
  \[ n_{si}^* = n \cdot v_1 + n \cdot n_{tt} \cdot n_{sc} = n(v_1 + n_{tt} \cdot n_{sc}) \]

- Reduction
  \[ \eta = \frac{n_{si} - n_{si}^*}{n_{si}} = 1 - \left( \frac{v_1}{\sum_{j=1}^{m} v_j \cdot n_{sc}} + \frac{1}{v_j} \right) \]

Application

5 Timetables
- 11, 12, 14, 16, 18 trains/h

10 Primary delay values
- 1,...,10 minutes

5 Infrastructure scenarios

\[ \eta = 89.86\% \]
The case study
### Case study

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Junction stationing</th>
<th>Tracks in Delft</th>
<th>Speed limit in Delft (km/h)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>North Delft</td>
<td>2 (Viaduct)</td>
<td>100</td>
<td>Current state</td>
</tr>
<tr>
<td>Phase 2</td>
<td>North Delft</td>
<td>2 (Tunnel)</td>
<td>140</td>
<td>Under construction (2015)</td>
</tr>
<tr>
<td>Phase 3</td>
<td>South Delft</td>
<td>4 (Tunnel)</td>
<td>140</td>
<td>Planned</td>
</tr>
<tr>
<td>Phase 4</td>
<td>None</td>
<td>4 (Tunnel)</td>
<td>140</td>
<td>Hypothetical</td>
</tr>
<tr>
<td>ETCS L1</td>
<td>North Delft</td>
<td>2 (Viaduct)</td>
<td>100</td>
<td>Hypothetical</td>
</tr>
</tbody>
</table>
Case study: Line The Hague – Rotterdam

- 4-2 tracked
- Mixed passenger traffic
- 11 trains/h
- Cyclic timetable

- Primary delay: (1,...,10) min Den Haag HS
- Delay threshold: 60 s
- Timing points: Rotterdam Centraal
- Simulation: OpenTrack
- Dispatching: FCFS
Micro-simulation based analysis of railway lines robustness

- Phase 1: Delft Viaduct – 2 tracks
- Phase 2: Delft Tunnel – 2 tracks
- Phase 3: Delft Tunnel – 4 tracks
- Phase 4: Entirely 4 tracks infrastructure
- Signalling works: ETCS Level 1

Capacity consumption

<table>
<thead>
<tr>
<th>Phase</th>
<th>Capacity Consumption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (11 trains/h)</td>
<td>81%</td>
</tr>
<tr>
<td>B (12 trains/h)</td>
<td>72%</td>
</tr>
<tr>
<td>C (14 trains/h)</td>
<td>71%</td>
</tr>
<tr>
<td>D (16 trains/h)</td>
<td>74%</td>
</tr>
<tr>
<td>E (18 trains/h)</td>
<td>78%</td>
</tr>
</tbody>
</table>

Legend: A (11 trains/h), B (12 trains/h), C (14 trains/h), D (16 trains/h), E (18 trains/h)
Total delay

- Phase 1: Delft Viaduct – 2 tracks
- Phase 2: Delft Tunnel – 2 tracks
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Settling time

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Diagram showing settling time at Rtd and primary delay at Gv as a function of time. Graphs comparing settling time amplification factor with frequency [train/s].
Share of trains involved

- Phase 1: Delft Viaduct – 2 tracks
- Phase 2: Delft Tunnel – 2 tracks
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Average delay per train

\[ y = ax + b \]

\[ x(y = 0) = -\frac{b}{a} \]

<table>
<thead>
<tr>
<th>Scenario</th>
<th>a</th>
<th>b</th>
<th>x (y=0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>36,84</td>
<td>-103,67</td>
<td>2,81</td>
</tr>
<tr>
<td>Phase 2</td>
<td>37,42</td>
<td>-121,57</td>
<td>3,25</td>
</tr>
<tr>
<td>Phase 3</td>
<td>38,00</td>
<td>-120,49</td>
<td>3,17</td>
</tr>
<tr>
<td>Phase 4</td>
<td>39,53</td>
<td>-156,26</td>
<td>3,95</td>
</tr>
<tr>
<td>ETCS lev. 1</td>
<td>34,18</td>
<td>-90,933</td>
<td>2,66</td>
</tr>
</tbody>
</table>

- Phase 1: Delft Viaduct – 2 tracks
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- Signalling works: ETCS Level 1
Robustness indices

Capacity consumption UIC406

Frequency [trains/h]

Capacity Consumption

40%  50%  60%  70%  80%  90%  100%

11  12  13  14  15  16  17  18

Recovery time

Settling time amplification factor

Frequency [trains/s]

Normalized total delay sensitivity indicator

Normalized total delay sensitivity indicator

0,00  0,50  1,00  1,50  2,00  2,50  3,00  3,50  4,00

11  12  13  14  15  16  17  18

Share of trains delayed

Delays trains amplification factor

Frequency [trains/s]

Normalized total delay sensitivity indicator

Normalized total delay sensitivity indicator

0,00  0,50  1,00  1,50  2,00  2,50  3,00  3,50  4,00

11  12  13  14  15  16  17  18

Signalling works: ETCS Level 1

Phase 1: Delft Viaduct – 2 tracks
Phase 2: Delft Tunnel – 2 tracks
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Conclusions
and further work
## Conclusions

Infrastructure scenarios comparison

<table>
<thead>
<tr>
<th>Traffic volume increase:</th>
<th>+ Total delay</th>
<th>+ Share of trains involved</th>
<th>≈ Recovery Time</th>
<th>= Average delay per train</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Capacity consumption (UIC 406)</th>
<th>not exhaustive for robustness</th>
</tr>
</thead>
</table>

The less timetable allowance, the wider indices spread

Micro-simulation based depends on timetables

Computational load

Dispatching on open line Vs. routing within at stations
Future work

- Timetable generation
- Dispatching / rerouting / rescheduling
- Correlation between Capacity consumption – Timetable allowance and the indicators spread
- Quantification of the loss in information given by the skimming method
- Go stochastic
Tunnel Inaugurated 28/2/2015

Viaduct

Tunnel