Robustness and Resilience of Multi-Modal Public Transport Networks

Oded Cats, Menno Yap and Niels van Oort
Outline

• Importance and challenges
• Identifying critical links
• Measuring the impact of disruptions
• Accounting for exposure
• Understanding disruption dynamics
• Value of increased capacity
• On-going and research outlook
Why public transport vulnerability?

- Recurring, costly and induce disproportional uncertainty
  [e.g. cost of PT disturbances in Stockholm region = 650 million €]

- Limited transferability from car networks
  - Interaction between infrastructure and service layers
  - Multi-modality, importance of transfers
  - Spatial and temporal availability
  - Lower connectivity
  - Operational constraints
  - Centralized control and management

- PT investments increasingly driven by reliability, congestion and vulnerability considerations

- Diversity: exogenous/endogenous; planned/unplanned; link/line
Limitations current approach robustness

- Everyone knows the costs of robustness measures, but:
  - Hardly insights in (societal) costs of disturbances
  - Hardly insights in (societal) benefits of measures aiming at improving PT robustness
- Focus on small disturbances which do not influence infrastructure availability
- Focus on mono-level / mono-operator PT networks

Vulnerable links from a passenger perspective

- Link vulnerability and robustness
  - From a passenger perspective, link vulnerability is the product of
    - Frequency
    - Duration
    - Impact

- For PT networks, a method is lacking to identify the most vulnerable links in the network from a passenger perspective: analogy road networks
  - Disturbances on the link itself → first-order effects
  - Spillback effects → second-order effects
  - Approximation of impact of disturbances using the I/C ratio → passenger volume
Identification of vulnerable links

- Developed method to identify the most vulnerable links in the multi-level PT network:
Case study Randstad Zuidvleugel (1)

- Expected blocked time for train link segments ≪ metro / light rail and tram
- On average: expected blocked time on tram links The Hague > Rotterdam
- Expected blocked time on metro / light rail links The Hague > Rotterdam
  - Switch density metro network Rotterdam > light rail network The Hague
Case study Randstad Zuidvleugel (2)

- Most vulnerable links are from different network levels
- Train links are vulnerable because of the large impact on many passengers
- Metro/light rail and tram links suffer more often from disturbances than train
- Busy metro / light rail and tram links are especially vulnerable
Case study RR Laan van NOI – Forepark

- Costs and benefits of robustness measures expressed in monetary terms

- Temporary extra IC stops:
  - Waiting time ↓
  - In-vehicle time + discomfort ↑

- Extra switches
  - Travel time ↓
  - Infrastructure costs ↑

<table>
<thead>
<tr>
<th>Link segment</th>
<th>Measure</th>
<th>Total costs 10 years (€*10⁶)</th>
<th>Effect on societal costs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laan van NOI - Forepark</td>
<td>No measure</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>Laan van NOI - Forepark</td>
<td>Extra IC stops</td>
<td>3.9</td>
<td>- 8%</td>
</tr>
<tr>
<td>Laan van NOI - Forepark</td>
<td>Switches</td>
<td>5.8</td>
<td>+ 35%</td>
</tr>
</tbody>
</table>
Exposing the role of exposure

- Link criticality depends on both impacts when a disruption occurs as well as the likelihood of its occurrence
- Difficult to obtain and analyse data concerning disruptions
- Estimate frequencies and durations of various disruption types
- Link-specific parameters based on length, veh-km, crossings...
- Static assignment: OmniTRANS, frequency-based TAM

Identifying critical links
Passenger load vs. Passenger exposure

1. Rotterdam Centraal - Schiedam Centrum
2. Rotterdam Zuid - Rotterdam Lombardijen
3. Rotterdam Lombardijen - Barendrecht
4. Rotterdam Blaak - Rotterdam Zuid
5. Rotterdam Centraal - Rotterdam Blaak

Exposure

1. Ternoot - Laan van NOI (T)
2. Laan van NOI - Voorburg 't Loo (R)
3. Spui - Grote Markt (T)
4. Grote Markt - Brouwersgracht (T)
5. Rijnhaven – Maashaven (M)
## Evaluating link criticality

### Passenger load vs. Passenger exposure

<table>
<thead>
<tr>
<th>Link Segment</th>
<th>Mode</th>
<th>Welfare change [€]</th>
<th>Ranking based on impact for an average disruption $c_l$</th>
<th>Annual expected welfare change [€/year]</th>
<th>Ranking based on annual expected impact, $E(c_l)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotterdam Zuid - Rotterdam Lombardijen</td>
<td>Train</td>
<td>€ 64 102</td>
<td>1</td>
<td>€ 11 574</td>
<td>9</td>
</tr>
<tr>
<td>Rotterdam Centraal - Rotterdam Zuid</td>
<td>Train</td>
<td>€ 56 183</td>
<td>2</td>
<td>€ 30 499</td>
<td>6</td>
</tr>
<tr>
<td>Rijswijk - Delft</td>
<td>Train</td>
<td>€ 56 180</td>
<td>3</td>
<td>€ 26 045</td>
<td>7</td>
</tr>
<tr>
<td>Rotterdam Centraal - Schiedam Centrum</td>
<td>Train</td>
<td>€ 39 385</td>
<td>4</td>
<td>€ 11 287</td>
<td>10</td>
</tr>
<tr>
<td>Rijnhaven – Zuidplein</td>
<td>Metro</td>
<td>€ 33 489</td>
<td>5</td>
<td>€ 266 235</td>
<td>3</td>
</tr>
<tr>
<td>Rotterdam Lombardijen - Barendrecht</td>
<td>Train</td>
<td>€ 27 134</td>
<td>6</td>
<td>€ 14 885</td>
<td>8</td>
</tr>
<tr>
<td>Ternoot - Laan van NOI</td>
<td>Tram</td>
<td>€ 26 840</td>
<td>7</td>
<td>€ 931 873</td>
<td>1</td>
</tr>
<tr>
<td>Laan van NOI – Forepark</td>
<td>Light rail</td>
<td>€ 14 175</td>
<td>8</td>
<td>€ 281 226</td>
<td>2</td>
</tr>
<tr>
<td>Melanchtonweg – Pijnacker Zuid</td>
<td>Light rail</td>
<td>€ 13 931</td>
<td>9</td>
<td>€ 189 173</td>
<td>4</td>
</tr>
<tr>
<td>Brouwersgracht – CS</td>
<td>Tram</td>
<td>€ 10 038</td>
<td>10</td>
<td>€ 176 821</td>
<td>5</td>
</tr>
</tbody>
</table>
Capturing disruption dynamics

- Static model: underestimation of disruption effects
- En-route decisions, imperfect information
- Both passengers and operators can respond to disruptions

*Spill-over*—secondary effects caused by either supply processes or passenger rerouting

*Upstream*—vehicles progress until they queue upstream of the link closure

*Downstream*—can reconsider and revise their travel decisions

*Stranded passengers*—on-board passengers are unable to alight and have to wait until the service is restored

Where shall we increase capacity?

### Evaluation example

<table>
<thead>
<tr>
<th>Stockholm case study</th>
<th>Disruption (D-Blue)</th>
<th>Relative travel times change due to disruption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Capacity enhancement (C-Green)</strong></td>
<td>No</td>
<td>$w(0,0)$</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>$w(\delta,0)$</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>$w(0,h)$</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>$w(\delta,h)$</td>
</tr>
</tbody>
</table>

Relative change in total travel times due to capacity enhancement:

- No: $-24.67\%$
- Yes: $-27.69\%$

Welfare gain increase from 1.7 to 2.0 million Swedish Crowns for all passengers during a single rush hour of operations.
Evaluating the robustness value of new investments

- Comparing alternative (baseline and extended) networks performance in case of disruptions

- Normal operations: LRT welfare gain of 150,000 SEK during a single rush hour

- Disruptions:
  - Critical links: welfare loss of 470,000-760,000 SEK, better off with LRT;
  - LRT: slightly worse-off than without it

- Incorporating into cost-benefit analysis

Plenty of open questions!

- What characterizes robust network design? (structure, operations)
- How can we incorporate robustness into project appraisal?
- What are the short-term and long-term impacts of disruptions on traveller behaviour?
- How can we analyse and shorten the recovery period?
- Not only complete breakdown – partial reductions
- How can we support the deployment of real-time operational mitigation measures and resource allocation?
- Multi-layer multi-modal network vulnerability
- ...

Suggestions on how together make it a robust research plan?

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