Effects of stochasticity on recovery solutions in the case of high-density rail/metro networks

Antonio Placido – Luca D’Acierno – Marilisa Botte – Bruno Montella
Outline

• Introduction

• Framework of the proposed procedure
  – Travel demand assignment to a microscopic simulation of the network
  – Dwell time estimation as flow dependent
  – Stability assessment of recovery strategies

• Applications to a real metro line

• Conclusions and research prospects
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Introduction

Rail metro networks represent the main public transportation system in high-density congested cities.
For this reason, when disruptions occur, dispatchers have to react appropriately and promptly so as to implement strategies which guarantee service operations even in degraded conditions.

In this context, rail simulation models are vital to analyse effects of feasible strategies on the service and compare the robustness of different solutions.

In the literature, there are several examples of recovery models and algorithms for railway rescheduling (Cacchiani et al., 2013).
Introduction
- Key aspects to take into account -

• Travel demand must be considered:
  ➢ To increase service quality
  ➢ To propose feasible strategies (Kanai et al., 2011)

• Stability Assessment of the recovery strategies proposed:
  ➢ Stability of the solutions during the real implementation (Quaglietta et al., 2013)
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Framework of the proposed approach - Analytical formulation -

\[
\hat{y} = \arg \min_{y \in S_y} Z(y, fc, tnp, rnp, td)
\]

System of models

\[
Z(y, fc, tnp, rnp, td) = 
\left( \beta_{\text{waiting}} \cdot \sum_{s=\text{station}} \sum_{p=\text{platform}} \sum_{r=\text{run}} \frac{tw^r_{s,p}(y, fc, tnp, rnp)}{fW^r_{s,p}(td)} \cdot fW^r_{s,p}(fd) + \right) \cdot Vot
\]

Symbols:
- \( y \): operational strategy
- \( y^\wedge \): optimal operational set
- \( S_y \): feasibility set of \( y \)
- \( Z \): objective function to be minimised
- \( fc \): failure context
- \( tnp \): transportation network performance
- \( rnp \): rail system network performance
- \( td \): travel demand

\begin{align*}
\beta_{\text{waiting}} &= \text{relevance given to waiting times} \\
\beta_{\text{on-board}} &= \text{relevance given to on-board times} \\
tw &= \text{waiting time} \\
fw &= \text{waiting (passenger) flow} \\
fb &= \text{on-board (in-vehicle) (passenger) flow} \\
Vot &= \text{value of time}
\end{align*}
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Framework of the proposed approach
- System of models -

Failure Simulation Model

Service Simulation Model

Pre-Platform demand Model

On-Platform demand Model

Travel Demand Model

Supply Model

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Framework of the proposed approach
- Failure Simulation Model -

RAMS analysis

Breakdown

Failure Simulation Model

Effects

Rail infrastructure

Signalling system

Rolling stock

R = Reliability
A = Availability
M = Maintainability
S = Safety
Framework of the proposed approach
- Interaction between Supply and Pre-Platform Demand Model-

Pre-Platform demand Model

Supply Model

User pre-platform choices

Passenger arrival rate to the platform

Literature: Cascetta (2009)
Effects of stochasticity on recovery solutions in the case of high-density rail/metro networks

Framework of the proposed approach
- Service Simulation Model -

Service Simulation Model ➔ Microscopic simulation software ➔ Rail system performances

Why a microscopic simulation?

• Simulation of the dynamic of network loading
• Feasible simulation of the rail system
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Dynamic Passenger Assignment
- On-Platform Model -

On-Platform demand Model

\[
\begin{align*}
\{ & d^t_{0_1-d_1} \quad d^t_{0_2-d_2} \\
\{ & \text{Arrival flow} = \text{Waiting flow} \\
\{ & d_{0_1-d_1} \quad d_{0_2-d_2} \\
\{ & \text{Not boarding flow} \\
\{ & d^t_{0_1-d_1} \quad d^t_{0_2-d_2} \\
\{ & \text{Residual capacity RC} = \text{Boarding flow} \\
\{ & d^{t+1}_{0_1-d_1} \quad d^{t+1}_{0_2-d_2} \\
\{ & \text{New arrival flow} \\
\{ & d^t_{0_1-d_1} \quad d^t_{0_2-d_2} \\
\{ & \text{Not boarding flow}
\end{align*}
\]

Dwell time estimation

Dynamic Passenger Assignment
- Dwell Time Estimation -

Door choice model (Kunimatsu et al., 2012)
Best exit point
Adjacent door
Adjacent coach

\[
\text{Alighting matrix} \quad \begin{array}{c|c|c}
\text{Door } j & \text{Destination } i \\
\hline
\text{Destination } i & \text{Boarding matrix} & \text{Total matrix} \\
& \text{Door } j & \text{Door } j \\
\hline
\text{Destination } i & \text{Door } j & \text{Most loaded door} \\
\end{array}
\]
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Dynamic Passenger Assignment - Dwell Time Estimation Function (1/2) -


Dynamic Passenger Assignment - OPM 1.0 -

Service Simulation Model

On-Platform demand Model

TRAVEL DEMAND MODULE

ROLLING STOCK MODULE

RAIL SERVICE MODULE

LOAD DIAGRAMS

PASSENGER TRIP INFORMATION

PLATFORM CONGESTION

Surveyed data
Gamma function
50th percentile
85th percentile

Travel demand

0.0000
0.0002
0.0004
0.0006
0.0008
0.0010
0.0012

0 500 1,000 1,500 2,000 2,500

OPM 1.0

Frequency

TRAVEL DEMAND MODULE

LOAD DIAGRAMS

PASSENGER TRIP INFORMATION

PLATFORM CONGESTION
Dynamic Passenger Assignment
- DwTE 1.0 -

Service Simulation Model

On-Platform demand Model

Fixed point

DwTE 1.0

PASSENGER FLOW MODULE

ROLLING STOCK AND STATION CONFIGURATION MODULE

DwTE ESTIMATION MODULE

Dwell Times

Crowding Level of Coaches

Dynamic Passenger Assignment
- OpenTrack and OPM 1.0 + DwTE 1.0 -

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Robustness assessment of recovery strategies - Implementation of a stochastic phase -

Deterministic phase

Set of optimal solution

Stochastic Phase

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Applications to a real metro line
- Line 1 of Naples metro system (Italy) -


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Applications to a real metro line
- Line 1 of Naples metro system (Italy) -

Simulated service:
From 6 to 21: 1 train every 8 minutes;
From 21 to 23.30: 1 train every 14 minutes

Rolling stock features:
Maximum capacity of trains: 864 pax
Maximum capacity of coaches: 216 pax

Breakdown context:
Maximum speed of a train 45 km/h

Stations with points and recovery track
Applications to a real metro line
- Randomness of the failure -

Exhaustive approach for the selection of recovery strategies

Failure 1 (strategy)
- Colli Aminei (outward trip)
- Medaglie d’Oro (outward trip)
- Garibaldi
- Medaglie d’Oro (return trip)
- Colli Aminei (return trip)
- Piscinola

Failure 2 (strategy)
- Medaglie d’Oro (outward trip)
- Garibaldi
- Medaglie d’Oro (return trip)
- Colli Aminei (return trip)
- Piscinola

Failure 3 (strategy)
- Garibaldi
- Medaglie d’Oro (return trip)
- Colli Aminei (return trip)
- Piscinola

Failure 4 (strategy)
- Medaglie d’Oro (return trip)
- Colli Aminei (return trip)
- Piscinola

Failure 5 (strategy)
- Colli Aminei (return trip)
- Piscinola
Applications to a real metro line
- Different travel demand pattern profiles -

### Applications to a real metro line
- Results of the deterministic phase (1/2) -

<table>
<thead>
<tr>
<th>Failure 1</th>
<th>Travel Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td>50(^{th}) percentile</td>
</tr>
<tr>
<td>Colli Aminei (outward trip)</td>
<td>€ 587,464</td>
</tr>
<tr>
<td>Medaglie d’Oro (outward trip)</td>
<td>€ 586,201</td>
</tr>
<tr>
<td>Garibaldi</td>
<td>€ 578,208</td>
</tr>
<tr>
<td>Medaglie d’Oro (return trip)</td>
<td>€ 578,361</td>
</tr>
<tr>
<td>Colli Aminei (return trip)</td>
<td>€ 578,001</td>
</tr>
<tr>
<td>Piscinola</td>
<td>€ 577,305</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Failure 2</th>
<th>Travel Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td>50(^{th}) percentile</td>
</tr>
<tr>
<td>Medaglie d’Oro (outward trip)</td>
<td>€ 579,901</td>
</tr>
<tr>
<td>Garibaldi</td>
<td>€ 573,205</td>
</tr>
<tr>
<td>Medaglie d’Oro (return trip)</td>
<td>€ 572,364</td>
</tr>
<tr>
<td>Colli Aminei (return trip)</td>
<td>€ 572,309</td>
</tr>
<tr>
<td>Piscinola</td>
<td>€ 572,208</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Failure 3</th>
<th>Travel Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td>50(^{th}) percentile</td>
</tr>
<tr>
<td>Garibaldi</td>
<td>€ 573,134</td>
</tr>
<tr>
<td>Medaglie d’Oro (return trip)</td>
<td>€ 572,293</td>
</tr>
<tr>
<td>Colli Aminei (return trip)</td>
<td>€ 572,238</td>
</tr>
<tr>
<td>Piscinola</td>
<td>€ 572,137</td>
</tr>
</tbody>
</table>

Effects of stochasticity on recovery solutions in high-density rail/metro networks

Applications to a real metro line
- Results of the deterministic phase (1/2) -

<table>
<thead>
<tr>
<th>Failure 4</th>
<th>Travel Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td>50&lt;sup&gt;th&lt;/sup&gt; percentile</td>
</tr>
<tr>
<td>Medaglie d’Oro (return trip)</td>
<td>€572,256</td>
</tr>
<tr>
<td>Colli Aminei (return trip)</td>
<td>€572,195</td>
</tr>
<tr>
<td>Piscinola</td>
<td>€572,077</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Failure 5</th>
<th>Travel Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strategy</strong></td>
<td>50&lt;sup&gt;th&lt;/sup&gt; percentile</td>
</tr>
<tr>
<td>Colli Aminei (return trip)</td>
<td>€572,364</td>
</tr>
<tr>
<td>Piscinola</td>
<td>€572,211</td>
</tr>
</tbody>
</table>

Applications to a real metro line - Dwell time estimation -

**From Piscinola to Garibaldi**

- **Fixed Dwell Time**
- **Dwell time of Train 2**

**From Garibaldi to Piscinola**

- **Fixed Dwell Time**
- **Dwell time of Train 2**
Applications to a real metro line
- Determination of the average departure delay -

Effects of stochasticity on recovery solutions in the case of high-density rail/metro networks


From Piscinola to Garibaldi

Estimation of departure delay

Dwell Time [sec]

0 10 20 30 40 50 60 70

Piscinola Chiaiano Frullone Coll Aniene Polyclinico Rione Alto Montedonzelli Medaglie d’Oro Vanvitelli Quattro Giorante Salvator rosa Materdei Museo Dante Toledo Universita Garibaldi

Fixed Dwell Time

Dwell time of Train 2

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## Applications to a real metro line
- Results of the stochastic phase (100 simulations) -

<table>
<thead>
<tr>
<th>Failure 1</th>
<th>Travel Demand</th>
<th>50&lt;sup&gt;th&lt;/sup&gt; percentile</th>
<th>95&lt;sup&gt;th&lt;/sup&gt; percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colli Aminei (outward trip)</td>
<td>-</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Garibaldi</td>
<td>0%</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Colli Aminei (return trip)</td>
<td>0%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Piscinola</td>
<td>100%</td>
<td>0%</td>
<td></td>
</tr>
</tbody>
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<table>
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<tr>
<th>Failure 2</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Medaglie d’Oro (outward trip)</td>
<td>-</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Medaglie d’Oro (return trip)</td>
<td>16%</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Colli Aminei (return trip)</td>
<td>26%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Piscinola</td>
<td>58%</td>
<td>0%</td>
<td></td>
</tr>
</tbody>
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<table>
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<tr>
<th>Failure 3</th>
<th>Travel Demand</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Medaglie d’Oro (return trip)</td>
<td>14%</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>Colli Aminei (return trip)</td>
<td>26%</td>
<td>28%</td>
<td></td>
</tr>
<tr>
<td>Piscinola</td>
<td>60%</td>
<td>52%</td>
<td></td>
</tr>
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<th>95&lt;sup&gt;th&lt;/sup&gt; percentile</th>
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</thead>
<tbody>
<tr>
<td>Medaglie d’Oro (return trip)</td>
<td>8%</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Colli Aminei (return trip)</td>
<td>28%</td>
<td>24%</td>
<td></td>
</tr>
<tr>
<td>Piscinola</td>
<td>64%</td>
<td>72%</td>
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<tr>
<td>Colli Aminei (return trip)</td>
<td>24%</td>
<td>14%</td>
<td></td>
</tr>
<tr>
<td>Piscinola</td>
<td>76%</td>
<td>86%</td>
<td></td>
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# Applications to a real metro line

- Analysis of the results -

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Conclusions

- Rail service management taking into account service quality

- Interaction between travel demand and rail services

- Fixed-point problem related to the dwell time calculation

- Stability assessment of recovery solutions
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Research prospects

- Integration of OPM 1.0 and DwTE 1.0 within a microscopic simulation software (i.e. Opentrack with API or other academic software)

- Improve the door choice model (Fuzzy logic)

- Apply the method in the case of larger and more complex rail networks
Thanks for your attention

Antonio Placido

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