Train rescheduling and rolling stock circulation in case of complete blockade for an urban rail transit line

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OUTLINE

- Background
- Model
- Solution approach
- Case study
- Conclusions
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● Background

● Model

● Solution approach

● Case study

● Conclusions
1. Background

- Large scale network
- Small headway
- Disruptions → serious impacts for passengers and operators
- Huge passenger demand
- High level of automation

Disruptions lead to serious impacts for passengers and operators in large scale networks, small headways, and high levels of automation.
1. Background

In 2017, Jul-Aug, 8 disruptions occurred:

- 08:19 Failure of turnout equipment (15min, Line 1)
- 07:14 Failure of equipment (25min, Line 10)
- 18:52 Failure of trains (15min, Line 9)
- 07:14 Failure of signal (30min, Line 10)
- 08:27 Failure of signal (15min, Line 6)
- 13:46 Passenger entering the track (30min, Line 2)
- 07:33 Failure of signal (40min, Line 5)
- 19:52 Passenger entering the track (15min, Line 2)

In total, 8 disruptions occurred from 07:03 to 08:27.
1. Background

On-board congestion
Disruptions cause trains stopping in open tracks (passenger cannot get off)

Passenger flow limitation
Disruptions cause passenger waiting outside the station (capacity is limited)

Traffic jams outside
Disruptions cause disordered operation of metro network, even traffic jams in the area

Effective rescheduling is important for enhancing subway performance under disruptions
1. Background

2017/5/13, 12:50, suicide occurred at station PGY in Line 1

- Measures and effects (dispatchers)
  - Power cutoff for contact rails
  - Manual driving in section with accident
  - Power supply recovered at 12:58
  - 1 service cancelled, 7 services delayed, 1 services added and 13 services adjusted
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2. Model

Set-up

- A complete blockade for both tracks
- Long blocking time, e.g., 30 min, 1 hour or more
- Short-turning services should be provided for both parts
- Expected headways based on passenger demand, rolling stocks, etc.
2. Model

Objective

- Minimize deviations between optimized headways and expected headways
- Minimize variations between consecutive headways
- Minimize number of rolling stocks
2. Model

**Objective function**

\[
F = \rho_1 \cdot \left( \sum_{i \in I \setminus I_{\text{total}}} |h_{i,j}^{\text{up}} - H| + \sum_{l \in L \setminus L_{\text{total}}} |h_{l,j}^{\text{dn}} - H| \right) \\
+ \rho_2 \cdot \left( \sum_{i \in I \setminus I_{\text{total}}, l_{\text{total}}} \sum_{j \leq K} (h_{i,j}^{\text{up}} - (h_{i-1,j}^{\text{up}} + h_{i+1,j}^{\text{up}})/2) + \sum_{l \in L \setminus L_{\text{total}}, l_{\text{total}}} \sum_{j \leq K} (h_{l,j}^{\text{dn}} - (h_{l-1,j}^{\text{dn}} + h_{l+1,j}^{\text{dn}})/2) \right) \\
- \rho_3 \cdot \sum_{i \in I, l \in L} \zeta_{i,l}
\]
2. Model

Departure and arrival constraints

\[ t_{\text{dwell}, \text{up}}^{i, j} \leq t_{i, j}^{\text{min}} \leq t_{i, j}^{\text{max}} \leq t_{\text{dwell}, \text{up}}^{i, j} \]

\[ t_{\text{dwell}}^{i, j} \leq t_{i, j}^{\text{dwell}, \text{up}} \leq t_{\text{dwell}}^{\text{max}} \]

i: train service in the up direction
l: train service in the down direction
j: station
2. Model

**Departure and arrival constraints**

A train can only enter a station when a predecessor train has left.

\[
\begin{align*}
    t_{l,j}^{\text{dep,dn}} &\leq t_{l',j}^{\text{arr,dn}}, l' > l \\
    t_{i,j}^{\text{dep,up}} &\leq t_{i',j}^{\text{arr,up}}, i' > i
\end{align*}
\]
2. Model

Headway constraints

- Calculation of headways

\[ h_{i,j}^{up} = t_{i+1,j}^{dep,up} - t_{i,j}^{dep,up}, \forall i \in \{1, 2, \ldots, I_{\text{total}} - 1\}, \forall j \in \{1, 2, \ldots, K\}, \]

\[ h_{i,j}^{dn} = t_{i+1,j}^{dep,dn} - t_{i,j}^{dep,dn}, \forall i \in \{1, 2, \ldots, I_{\text{total}} - 1\}, \forall j \in \{1, 2, \ldots, K\}, \]

- Maximum and minimum headways

\[ h_{\text{min}} \leq h_{i,j}^{up}, \forall i \in \{1, 2, \ldots, I_{\text{total}} - 1\}, \forall j \in \{1, 2, \ldots, K\}, \]

\[ h_{\text{min}} \leq h_{i,j}^{dn}, \forall i \in \{1, 2, \ldots, I_{\text{total}} - 1\}, \forall j \in \{1, 2, \ldots, K\}. \]

The maximum headway between train services largely depends on the disruptions \( \rightarrow \) not include in the model.
2. Model

Rolling stock circulation constraints (turnaround station)

\[ \xi_{i,l} = \begin{cases} 
1, & \text{train service } i \text{ and } l \text{ are served by the same train which turnaround at station} \\
0, & \text{otherwise} 
\end{cases} \]

\[ \beta_l = \begin{cases} 
1, & \text{train service } l \text{ does not enter the depot} \\
0, & \text{otherwise} 
\end{cases} \]

\[ \alpha_i = \begin{cases} 
1, & \text{train service } i \text{ does not come from the depot} \\
0, & \text{otherwise} 
\end{cases} \]

\[ \alpha_i = \sum_{l \in L} \xi_{i,l}, \forall i \in \{1, 2, \ldots, I_{\text{total}}\}, \]

\[ \beta_l = \sum_{i \in I} \xi_{i,l}, \forall l \in \{1, 2, \ldots, L_{\text{total}}\}. \]

\[ \alpha_i + \beta_l \leq 2 + M(1 - \xi_{i,l}) \]

\[ \alpha_i + \beta_l \geq 2 - M(1 - \xi_{i,l}) \]
2. Model

Turnaround time constraints (turnaround stations)

\[
\begin{align*}
    t_{i,1}^{arr,up} - t_{i,1}^{dep,up} &\leq \tau_{\text{max}} + M(1 - \xi_{i,l}) \\
    t_{i,1}^{arr,up} - t_{i,1}^{dep,up} &\geq \tau_{\text{min}} - M(1 - \xi_{i,l}) \\
    t_{l+1,1}^{dep,dn} &\geq \sum_{i \in l} \xi_{i,l} t_{i,1}^{arr,up}
\end{align*}
\]
2. Model

Rolling stock circulation constraints (disrupted station)

- Train order at station K \( \theta_{i,l} = 1 \iff t_{l,K}^{\text{dep, dn}} - t_{i,K}^{\text{arr, up}} \leq 0 \), i arrives after l departing
- At most two trains dwell at station K \( 0 \leq N_{i}^{\text{arr}} - N_{i}^{\text{dep}} \leq 2 \)
  \( N_{i}^{\text{arr}} \) and \( N_{i}^{\text{dep}} \) are the number of train services which arrive at or depart from station K before the arrival of train service i, respectively
  \[
  N_{i}^{\text{dep}} = \sum_{l \in L} \theta_{i,l}, \quad N_{i}^{\text{arr}} = i - 1
  \]
- Dwell time at station K \( t_{i,K}^{\text{dwell, up}} \geq q \), \( q \) : minimal dwell time at station K
  Dwell time at station K involves the time for passenger boarding/alighting and the change-end time

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2. Model

Rolling stock circulation constraints (disrupted station)

- Safety headway for turnaround at station K

\[ t_{i,K}^{\text{arr,up}} - t_{l,K}^{\text{dep,dn}} \geq p - M(1 - \theta_{i,l}) \]
\[ t_{l,K}^{\text{dep,dn}} - t_{i,K}^{\text{arr,up}} \geq p - M \theta_{i,l} \]

- Rolling stock for train service i must turnaround at station K

\[ t_{l,K}^{\text{dep,dn}} \leq t_{i,K}^{\text{arr,up}} + t_{i,K}^{\text{dwell,up}} + M(1 - \sigma_{i,l}) \]
\[ t_{l,K}^{\text{dep,dn}} \geq t_{i,K}^{\text{arr,up}} + t_{i,K}^{\text{dwell,up}} - M(1 - \sigma_{i,l}) \]

\[ \sum_{i \in I} \sigma_{i,l} = 1 \]

\[ \sum_{l \in L} \sigma_{i,l} = 1 \]
Inventory constraints for the depot

- Limited rolling stocks available in the depot

\[ I_i^{\text{out}} - I_i^{\text{in}} \leq I_0 \]

- \( I_i^{\text{out}} \) --- number of exiting operations before the departure of train service \( i \) at station 1

- \( I_i^{\text{in}} \) --- number of entering operations before the departure of train service \( i \) at station 1
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3. Solution approach——MILP

Transformation properties

A logical variable times a real-valued variable

Consider $\tilde{f}_{\text{min}} = \min \tilde{f}$, $\tilde{f}_{\text{max}} = \max \tilde{f}$. By introducing a new real-valued variable $z = \delta \cdot \tilde{f}$, then nonlinear expression $\delta \cdot \tilde{f}$ is equivalent to

$$
\begin{align*}
    z &\leq \tilde{f}_{\text{max}} \cdot \delta, \\
    z &\geq \tilde{f}_{\text{min}} \cdot \delta, \\
    z &\leq \tilde{f} - \tilde{f}_{\text{min}} \cdot (1 - \delta), \\
    z &\geq \tilde{f} - \tilde{f}_{\text{max}} \cdot (1 - \delta).
\end{align*}
$$

Statement $[\tilde{f}(\bar{x}) \leq 0] \iff [\rho = 1]$

By introducing a new auxiliary logical variable $\rho \in [0,1]$, then

$$
[\tilde{f}(\bar{x}) \leq 0] \iff [\rho = 1] \text{ is true if } \begin{cases}
\tilde{f}(\bar{x}) \leq \tilde{f}_{\text{max}}(1 - \rho), \\
\tilde{f}(\bar{x}) \geq \varepsilon + (\tilde{f}_{\text{min}} - \varepsilon)\rho,
\end{cases}
$$

$\varepsilon$ is a small positive number
3. Solution approach——MILP

Transformation properties

- Absolute function

We consider introduce two new auxiliary real-valued variables $\zeta_{i,j}^{up}$ and $\zeta_{i,j}^{dn}$, the absolute function is equivalent to:

\[
\begin{align*}
\zeta_{i,j}^{up} & \geq h_{i,j}^{up} - H \\
\zeta_{i,j}^{up} & \geq H - h_{i,j}^{up} \\
\zeta_{l,j}^{dn} & \geq h_{l,j}^{dn} - H \\
\zeta_{l,j}^{dn} & \geq H - h_{l,j}^{dn}
\end{align*}
\]
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4. Case study

- Blockade starts at 7:10am and lasts to 8:30am at least
- Turnaround time should be between 120s and 720s
- The minimal headway is 120s (normal case)
- The expected headway during disruption period is set as 300s

<table>
<thead>
<tr>
<th>Number of train service</th>
<th>Direction</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>UP(1)</td>
<td>up</td>
<td>dwelling at TJNL</td>
</tr>
<tr>
<td>UP(2)</td>
<td>up</td>
<td>running from CQN to JHL</td>
</tr>
<tr>
<td>UP(3)</td>
<td>up</td>
<td>running from YZHCZ to CQ</td>
</tr>
<tr>
<td>DN(101)</td>
<td>down</td>
<td>dwelling at YZHCZ</td>
</tr>
<tr>
<td>DN(102)</td>
<td>down</td>
<td>running from CQN to CQ</td>
</tr>
<tr>
<td>DN(103)</td>
<td>down</td>
<td>running from TJNL to JHL</td>
</tr>
</tbody>
</table>
4. Case study

- Trains are forced to stop at stations until dispatcher takes actions
- Longer reaction time results larger delays

The reaction time of dispatcher is 5 min

The reaction time of dispatcher is 10 min
4. Case study

The reaction time of dispatcher is 5 min

- Dwell times of train services at stations are much longer in the beginning of the disruption
- 6 rolling stocks are required to satisfy the expected headway (same as rolling stocks on the line)
- Longer turnaround times for the station before the disrupted area (up → down)

The reaction time of dispatcher is 10 min
4. Case study

The reaction time of dispatcher is 5 min

- A longer reaction time results bigger headway variations
- The numbers of affected train services are the same
- The expected headway can be reached

The reaction time of dispatcher is 10 min
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Conclusions

- Effective disruption management algorithms are important for the daily operations

- A model is proposed to integrate the train rescheduling and rolling stock circulation in case of complete blockade

- The problem is transformed into an MILP problem and solved by CPLEX

- A small case study based on the Beijing Yizhuang line is performed
Conclusions

- Train traffic Management
  - Short-turning
  - Re-timing
  - C cancelling trains

- Passenger flow Management
  - Waiting
  - Boarding/alighting
  - Rerouting
  - Rejections

- Iterative disruption management
  - Alternative routes
  - Train dynamics
  - Line characteristics

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