Development of the Operational Stability and Efficiency Evaluation Model for Metro Systems

Yung-Cheng (Rex) Lai, Chi-Sang Ip and Shao-Yuan Huang
Railway Technology Research Center,
Department of Civil Engineering,
National Taiwan University
Operational Stability and Efficiency in Metro System

- There are three operational stability and efficiency components, which are Metro Service Plan, System Reliability and Maintainability, and System Characteristics.

![Diagram showing the relationship between Operational Stability and Efficiency, System Reliability and Maintainability, and Metro Service Plan.]
Glass cup theory – tradeoff between stability and efficiency

- Metro System
  - Capacity (Metro Assets)
  - Used Capacity (Assets Utilization)
  - Available Capacity (Slacks)
  - System Failure (Disruption)

- Glass
  - Size (Existing Resource)
  - Water Level (Resource Usage)
  - Empty Space (Buffer)
  - Vibration (Disruption)

Higher Assets Utilization May Cause Lower System Stability;
Lower Assets Utilization is a Waste of Capacity
Three types of stability evaluation are commonly used:

- Delay propagation statistics for various disturbance scenarios
- Permissible buffer time for trains before delaying other trains
  - Carey (1998), Salido et al. (2008), Cicerone et al. (2009)
- Required time until the initial plan is recovered
  - Goverde et al. (2009), Berbey et al. (2008, 2009)
- Li (2010)
  - Indicated that evaluating operational stability from delay perspective can lead to overestimated or underestimated results
  - Proposed a capacity and risk analyses based stability evaluation model
  - Used the average expected recovery time to evaluate timetable stability
  - Did not take the uncertainty of expected recovery time into account

Most of the Studies Evaluate Operational Stability from Delay Perspective
Operational Efficiency
- Assets Utilization Efficiency

Percentage of the Capacity Usage

\[ \eta = \frac{u}{C_{sc}} \times 100\% \]

where:
- \( \eta \): operational efficiency (%);
- \( u \): used capacity (trains/hour);
- \( C_{sc} \): normal capacity (trains/hour)
Operational Stability
- Expected Recovery Time

Volume (Trains/hour)
Available Capacity
Used Capacity

Recovery Time
Repair Time
Disturbed Trains

Expected Recovery Time = Probability of System Failures × Recovery Time
Evaluation Model

System Characteristics
- Capacity Analysis Module
  - Normal Capacity
  - Downgraded Capacity

Metro Service Plan
- Used Capacity

Historical Disturbance Data
- Reliability Module
  - Reliability Distribution
- Maintainability Distribution

Operational Stability and Efficiency Module
- Operational Stability
- Operational Efficiency

Mean and Variance of the Expected Recovery Time

Percentage of the Capacity Usage
Capacity Analysis Module

- **Normal Capacity**
  - The maximum number of *trains* that would be able to operate on a given *infrastructure* under a particular set of *operational conditions* during a specific time interval

- **Downgraded Capacity**
  - The *reduced capacity* due to *operational disruptions*

![Diagram showing the calculation of line capacity](image)
Reliability Module

- **Maintainability Distribution**
  - From historical disturbance data
  - Collect Mean Time To repair (MTTR), i.e. repair time
  - Use **cluster analysis** to categorize disturbance by the repair time

- **Reliability Distribution**
  - Mean time between failure (MTBF) collected from historical disturbance data

\[ R(t) = P(T \geq t) \]

- \( R(t) \) = system reliability of exposure \( t \);
- \( T \) = MTBF (operated train-hour); and
- \( t \) = exposure (operated train-hour).
Operational Stability and Efficiency Module

- System Characteristics
- Metro Service Plan
- Historical Disturbance Data
- Used Capacity
- Reliability Module
- Maintainability Distribution
- Operational Stability and Efficiency Module

- Normal Capacity
- Downgraded Capacity
- Reliability Distribution

- Mean and Variance of the Expected Recovery Time
- Percentage of the Capacity Usage
A case study was conducted for a metro system

- Service Plan
  - Weekday service plan
  - Weekend service plan

- System Characteristics
  - 24 intermediate stations
  - 2 terminal stations

- Historical Disturbance Data
  - Totally around 200 recorded disturbances were collected for a ten-month period

Operational Stability and Efficiency Evaluation Model

Inputs
- System Characteristics
- Service Plan
- Historical Disturbance Data

Outputs
- Mean and Standard Deviation of Expected Recovery Time
- Percentage of Capacity Usage
Determine the Maintainability

- By performing the **cluster analysis with repair time**
  - There are **7 types** of disturbance
  - Each type had its **MTTR**

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Mean Time to Repair</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train Failure Level 1</td>
<td>3.10</td>
</tr>
<tr>
<td>Train Failure Level 2</td>
<td>8.62</td>
</tr>
<tr>
<td>Loss of Electrical Power</td>
<td>11.01</td>
</tr>
<tr>
<td>Line Obstruction</td>
<td>7.89</td>
</tr>
<tr>
<td>Signal Failure</td>
<td>4.67</td>
</tr>
<tr>
<td>Communication Failure</td>
<td>13.98</td>
</tr>
<tr>
<td>Others</td>
<td>3.65</td>
</tr>
</tbody>
</table>
Determine the Reliability

- From the historical disturbance data
  - Failure rate $\lambda$ is calculated as the reciprocal of mean time between failures (MTBF)

- System Reliability $R(t)$ follow the exponential distribution

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>$\lambda$ (failure/train-hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train Failure Level 1</td>
<td>2.00E-04</td>
</tr>
<tr>
<td>Train Failure Level 2</td>
<td>2.18E-04</td>
</tr>
<tr>
<td>Loss of Electrical Power</td>
<td>3.12E-05</td>
</tr>
<tr>
<td>Line Obstructed</td>
<td>4.01E-05</td>
</tr>
<tr>
<td>Signal Failure</td>
<td>1.42E-04</td>
</tr>
<tr>
<td>Communication Failure</td>
<td>7.26E-05</td>
</tr>
<tr>
<td>Others</td>
<td>1.58E-05</td>
</tr>
</tbody>
</table>

$$R(t) = P(T \geq t) = 1 - e^{-\lambda t}$$

$\lambda = \text{Failure Rate}$

$t = \text{Exposure (train-hours)}$
# Overall Evaluation Results

<table>
<thead>
<tr>
<th></th>
<th>Weekday Service Plan</th>
<th>Weekend Service Plan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D1-bound</td>
<td>DR1-bound</td>
</tr>
<tr>
<td><strong>Expected Recovery Time (min)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.677</td>
<td>0.679</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.016</td>
<td>0.016</td>
</tr>
<tr>
<td><strong>Average Operational Efficiency (%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>30.37</td>
<td>31.53</td>
</tr>
</tbody>
</table>

**Substantial Increase (210%) in Expected Recovery Time with Relatively Small Increase (46%) in Operational Efficiency**
Operational Efficiency
3D-histograms (Weekend)

Relatively High Operational Efficiency Happen at Terminal Sections and Sections near Station BR4
Relatively High Expected Recovery Time is Observed at Terminal Sections and Sections near Station BR4
Operational Efficiency
3D-histograms (Weekday)

High Operational Efficiency Happen at Terminal Sections and Sections near Station BR4, Particularly in Peak Hours
Terminal Sections and Sections near Station BR4 Have High Expected Recovery Time, Particularly in Peak Hours
Operational Stability and Efficiency
Section Perspective (Weekday)

Highest Expected Recovery Time and Efficiency Occur at Sections near Station BR4; Uncertainty Increases with Expected Recovery Time
Operational Stability and Efficiency
Time Perspective (Weekday)

**Operational Stability and Efficiency**

**Expected Recovery Time (min)**

- **Average Expected Recovery Time**
- **Operational Efficiency**
- **2 Standard Deviation from the Average**

During Peak Hours:
- **Highest Expected Recovery Time and Efficiency**

**Operational Efficiency**

- **Expected Recovery Time (min)**
To Improve System Stability

Improve System Reliability & Maintainability

Operational Stability and Efficiency

System Reliability and Maintainability

System Characteristics
Metro Service Plan

Improve Capacity (Upgrade System)
Adjust Service Plan
### Expected Recovery Time Composition

#### Weekday Service Plan
- Train Failure Level 1: 0.173 min
- Train Failure Level 2: 0.526 min
- Loss of Electrical Power: 0.095 min
- Line Obstructed: 0.088 min
- Signal Failure: 0.185 min
- Others: 0.016 min
- Total: 1.356 min

#### Weekend Service Plan
- Train Failure Level 1: 0.055 min
- Train Failure Level 2: 0.169 min
- Loss of Electrical Power: 0.031 min
- Line Obstructed: 0.028 min
- Signal Failure: 0.060 min
- Others: 0.005 min
- Total: 0.438 min

#### Upgraded Total
- Weekday: 1.083 min
- Weekend: 0.348 min
- Reduction: -20%

**Mainly from Train Failure Level 2 and Communication Failure, Totally about 60%**.
Conclusions

• With the proposed method, metro operators can examine and monitor the **stability and efficiency** of their operational plan.

• **Stability** usually decreases with the increase of **efficiency**, and the proposed method can help users establish and understand this relationship between stability and efficiency.

• This methodology can also be used to **justify whether improvement strategies are cost effective or not**.
Thank you & Questions?

Railway Technology Research Center
Department of Civil Engineering
National Taiwan University

Website: http://www2.ce.ntu.edu.tw/~railway/

Telephone Number: +886-2-3366-4362
Email: yclai@ntu.edu.tw