Development of the Evaluation Process and Models for Metro System Service Stability and Efficiency

Yung-Cheng (Rex) Lai

14th September, 2012

Presentation at the William W. Hay Railroad Engineering Seminar
Research Interests

• Rail Transportation System
  – Railway Capacity Analysis (Service Performance & Evaluation)
  – Railway Operations and Management (Service Design)
  – Railway Safety

• Techniques:
  – Math Programming
  – Heuristic or Decomposition Methods
  – Simulations
Selected Research Topics on Rail Capacity

- **Capacity Evaluation & Computation**
  - Impact of Key Capacity Factors (heterogeneity, priority, etc.)
  - Development of Rail Capacity Models
  - *Capacity Utilization Efficiency & Stability*

- **Capacity Management & Investment**
  - Decision Support Framework for Strategic Capacity Planning
  - High Speed Route Improvement Optimizer
  - Optimization of Train Network Routing with Heterogeneous Traffic

*Development of the Evaluation Process and Models for Metro System Service Stability and Efficiency*
Glass Cup Theory – Tradeoff between Efficiency and Stability

• 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

Every System has its own “optimal balance”
Evaluation Framework and Models

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
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); and
- \( C_{sc} \): normal capacity (trains/hour)
Operational Stability
- Expected Recovery Time

- Traffic Flow (Trains/hour)
- Available Capacity
- Used Capacity

- Repair Time
- Disturbed Trains
- Recovery Time
- Normal Capacity
- Downgraded Capacity
- Service Plan (headway)

Disturbance

Time (Hour)

$T_1$, $T_2$, $T_3$, $T_4$, $T_5$
Expected Recovery Time = Risk in Capacity Utilization

Metro Operation Is Not Always Under Disruptions
System Instability Is Introduced Through the Concept of
Expected Value in Probability Theory

Expected Recovery Time $= \text{Probability of System Failures} \times \text{Recovery Time}$

$$F(t) = 1 - e^{-\lambda t}$$

$\lambda = \text{Failure Rate}$

$\text{Exposure (e.g. train-hours)}$
Repair Time Is Related to the System Maintainability

- Expected recovery time inherits uncertainty from the stochastic properties of maintainability
Evaluation Framework and Models

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

Metro Service Plan
- Used Capacity
  - Reliability Distribution
  - Maintainability Distribution

Historical Disturbance Data
- Reliability Module
- Maintainability Distribution

Operational Stability and Efficiency Module
- Mean and Variance of the Expected Recovery Time
- Operational Stability
- Operational Efficiency
- Percentage of the Capacity Usage
A Case Study was Conducted for a Metro System

- **Service Plan**
  - Weekday service plan
  - Weekend service plan

- **System Characteristics**
  - 20+ intermediate stations
  - 2 terminal stations

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

---

**Inputs**
- System Characteristics
- Service Plan
- Historical Disturbance Data

**Operational Stability and Efficiency Evaluation Model**

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

- The classification of disturbances can facilitate the improvement of operational performance as it provides information about the sources of instability.

<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>
The operational stability is composed of
- Severity of disturbances (Maintainability)
- Frequency of disturbances (Reliability)

<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>

\[
F(t) = 1 - e^{-\lambda t}
\]

\( \lambda \) = Failure Rate
\( t \) = Exposure (e.g. 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>Mean</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td></td>
<td>0.677</td>
<td>0.016</td>
</tr>
<tr>
<td><strong>Average Operational Efficiency (%)</strong></td>
<td>30.37</td>
<td>20.81</td>
</tr>
</tbody>
</table>

**Substantial Increase (>200%) in Operational Instability 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
Terminal Sections and Sections near Station BR4 have High Expected Recovery Time, particularly in Peak Hours
Operational Stability and Efficiency
Section Perspective (Weekday)

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

Highest Instability and Efficiency Occur During Peak Hours
Means to Improve System Stability

- Improve System Stability & Maintainability
- Operational Stability and Efficiency
  - System Reliability and Maintainability
  - System Characteristics
  - Metro Service Plan

- Improve Capacity (Upgrade System)
- Adjust Service Plan
Evaluation of Improvements

**Daily Expected Recovery Time (min)**

**Original**

**Communication System Upgraded**

- 1.356
- 1.083
- 0.31

-20%
Conclusions

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

• Operational instability usually increases with operational 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.
Future Work

- An **operational database** should be established to record and continuously update the disturbance data and system characteristics so as to understand the most up-to-date system reliability status.

- Future studies should focus on the determination of the **optimal balance** in operational stability and efficiency.
Thank you & Questions?

Yung-Cheng (Rex) Lai
Assistant Professor
Railway Technology Research Center
Department of Civil Engineering
National Taiwan University
E-mail: yclai@ntu.edu.tw
Phone: +886-2-3366-4243