MODELING SUBWAY RISK ASSESSMENT USING FUZZY LOGIC

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**SUBWAY CURRENT PRACTICES**

- Reno-Station I & II.
  - Structural and architectural renovations.
  - Age and Visual inspection only.

- 5-level evaluation, 9 functional Criteria, 1 “Physical and Structural” condition.

- KPI
  - (0-10) evaluation scale based upon 23 items.
  - From customer point of view.

- Ranking system based on 11 weighted factors (main 3).
  - Structural evaluation based on field inspection.
  - Constant weights per station.

- Used 7 criteria selection procedure.
  - Platform users
  - Visual aspect of station
  - Environment
  - Daily rider satisfaction.

**Literature review**
America’s public transit infrastructure plays a vital role in our economy, connecting millions of people with jobs, medical facilities, schools, shopping, and recreation, and it is critical to the one-third of Americans who do not drive cars. Unlike many U.S. infrastructure systems, the transit system is not comprehensive, as 45% of American households lack any access to transit, and millions more have inadequate service levels. Americans who do have access have increased their ridership 9.1% in the past decade, and that trend is expected to continue. Although investment in transit has also increased, deficient and deteriorating transit systems cost the U.S. economy $90 billion in 2010, as many transit agencies are struggling to maintain aging and obsolete fleets and facilities amid an economic downturn that has reduced their funding, forcing service cuts and fare increases.
State of Good repair = 2.5/5

Adopt comprehensive asset management systems to maximize investments
**SUBWAY NETWORK EFFORTS**

**Abu-Mallouh (1999)**
- Improved MTA NYCT model & developed MSRP model
- Used IP and AHP to optimize fund allocation.

**Semaan (2006)**
- Subway Station Diagnosis Index.
- Diagnose subway station and assess its condition state using an index.

**Farran (2006)**
- Developed M&RPPI model.
- Select the optimum rehabilitation action based on (LCC) for a single infrastructure element.

**Semaan (2011)**
- Developed SUPER model
- Evaluates structural performance of different components using performance curves.
**RESEARCH LIMITATIONS**

- **Functional Perspective**
  - Asset Level

- **Condition Assessment**
  - Deterioration Models
  - Asset/network level

- **Assess subway components**
  - Functional + Structural perspectives
  - Network Level
  - Easily adopted

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**Problem Statement**

**Risk Index**
Research techniques

Subway networks assessment

Probability of Failure model

Failure consequences

Consequence of failure model

Subway Network Hierarchy

Criticality factors

Infrastructure assets performance models

Budget allocation

Risk-based asset management

Fuzzy Risk Index Model

Model Validated?

Yes

Maintenance options

Risk Index

Cost Options

Risk-Based Budget Allocation Model
Probability of Failure Sub-Model
NETWORK HIERARCHY

Probability of Failure Model

Lines

Tunnels

Stations

Auxiliary structures

Bottom Slab

Walls

Dome

Walls

Stairs

Slabs

Slabs

Walls

Probability of Failure Model
Probability of Failure Model

Recent Network Data

Reliability-Based Weibull Cumulative function

System Modeling

Bottom Slab  Walls  Dome  Walls  Stairs  Slabs  Slabs  Walls

Tunnels  Stations  Auxiliary structures

Lines
The probability of failure model for stations is given by:

$$P_{\text{STA}_j} = 1 - \left[ \prod_{i=1}^{n} P_{\downarrow \text{STE}_i} P_{\downarrow \text{STL}_i} \right] \left[ \prod_{i=1}^{n} P_{\downarrow \text{SE}_i} P_{\downarrow \text{SI}_i} \right] \left[ \prod_{i=1}^{n} (1 - P_{\downarrow \text{WI}_i})(1 - P_{\downarrow \text{WE}_i}) \right]$$
TUNNELS

Probability of failure Model

\[ P_{\text{TUN}} = 1 - (1 - P_{\downarrow D}) \times (1 - P_{\downarrow w}) \times (1 - P_{\downarrow s}) \]
**Auxiliary Structure**

![Diagram of auxiliary structure]

The probability of failure model is given by

\[ P_{\text{Aux St}} = 1 - (1 - P_{\downarrow w}) (1 - P_{\downarrow TS} \ast P_{\downarrow BS}) \]
\[ P_{\text{line} \ z} = 1 - \left[ (1 - \prod_{i=1}^{n} P_{\text{STA} \ \downarrow i}) \times (1 - \prod_{i=1}^{n} P_{\text{TUN} \ \downarrow i}) \times (1 - \prod_{i=1}^{n} P_{\text{AUX} \ \downarrow i}) \right] \]
Probability of failure Model

\[ P_{\text{Net}} = \prod_{i=1}^{n} P_{\text{Line}i} \]
Consequence of Failure Sub-Model
Consequences of failure Model

NETWORK HIERARCHY

Lines

Tunnels

Stations

Auxiliary structures

Bottom Slab

Walls

Dome

Walls

Stairs

Slabs

Slabs

Walls
Consequences of failure

Financial Impacts
- Replacement/repair cost
- Revenue Loss

Social Impacts
- User traffic frequency
- Interruption Rate
- Service continuation

Operational Impacts
- Ease of providing alternative
- Time to repair
An Integrated Risk-based Asset Management Tool for Subway Systems

This survey estimates the relative importance of the expected consequences of failure and subway stations' criticality to be further used for risk assessment. The comparison between factors will be conducted using a pairwise comparison matrix and a scale that expresses the qualitative judgments between criteria numerically.

The scale indicates the relative importance of the two criteria (X) and (Y) preference through selecting the number that reflects your point of view.

4. With respect to “Social Impacts”, indicate the relative importance of impacts on each other.

5. With respect to “Operational Impacts”, indicate the relative importance of impacts on each other.

6. With respect to “Financial Impacts”, indicate the relative importance of impacts on each other.

7. With respect to “Social Impacts” of failure, indicate the relative importance of impacts on each other.

8. With respect to “Social Impacts of failure”, indicate the relative importance of impacts over each other.

9. With respect to “Operational Impacts of failure”, indicate the relative importance of impacts over each other.

10. Are there any other impacts of failure that the survey failed to address? If yes, please indicate them.

11. Based on your experience, what is the maximum allowable number of service interruptions per year to sustain a good service reputation? *
Consequence of failure Model

IMPACTS WEIGHTS

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Financial Impacts</td>
<td>F1: Revenue, F2: Replacement repair cost</td>
</tr>
<tr>
<td>2. Social Impacts</td>
<td>S1: Service continuation, S2: Interruption rate</td>
</tr>
<tr>
<td>3. Operational Impacts</td>
<td>S3: User traffic frequency</td>
</tr>
<tr>
<td></td>
<td>O1: Ease of Providing Alternative, O2: Time to repair</td>
</tr>
</tbody>
</table>

Global weight & Local weight
Criticality Index
NETWORK HIERARCHY

Criticality Index Model

Lines

Tunnels
- Bottom Slab
- Walls
- Dome

Stations
- Walls
- Stairs
- Slabs

Auxiliary structures
- Slabs
- Walls
Criticality Index Model

Criticality Index

Characteristics (C)
- C1: Number of Lines
- C2: Number of exits

Station Location (L)

Nature of use (N)
- N1: Intermodal Station
- N2: End Station
<table>
<thead>
<tr>
<th>Attraction type</th>
<th>Points of Interest</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Touristic Attractions</td>
<td>Museums, Theatres, Centre Infotouriste, Old Montreal and Old Port, Parks, Historical Sites, Squares, Malls</td>
<td></td>
</tr>
<tr>
<td>Sports</td>
<td>Arenas, Stadium, Clubs</td>
<td>Recreational</td>
</tr>
<tr>
<td>Culture</td>
<td>China Town, Cinemas, Libraries, Cemetery</td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td>Central Bus Station, inter-city rail station</td>
<td></td>
</tr>
<tr>
<td>Businesses</td>
<td>Commerce Chambers, Quartier International de Montréal</td>
<td></td>
</tr>
<tr>
<td>Worship Places</td>
<td>Churches, Mosques, Temples, Cathedral, Oratory</td>
<td>Vitalities</td>
</tr>
<tr>
<td>Educational</td>
<td>Schools, Universities, Colleges</td>
<td></td>
</tr>
<tr>
<td>Governmental</td>
<td>City Hall, Court</td>
<td></td>
</tr>
<tr>
<td>Health Care</td>
<td>Hospitals, CLSC’s, Health Institutes</td>
<td></td>
</tr>
<tr>
<td>Residence</td>
<td>Areas of high, medium, and low residence</td>
<td>Residence</td>
</tr>
</tbody>
</table>
Criticality Index Model

Characteristics (C)
- C1: Number of Lines
- C2: Number of exits

Station Location (L)
- L1: Recreational
- L2: Vital Locations
- L3: Residence Locations

Nature of use (N)
- N1: Intermodal Station
- N2: End Station
SECTION III: STATION CRITICALITY

Page description:
This section attempts to measure the relative criticality of subway stations. Based on the literature review and case studies, the factors contributing to station criticality were identified as illustrated in the following figure.

A. Main criteria comparison with respect to goal “Station Criticality”:
12. With respect to “Station Criticality”, indicate the relative importance of impacts over each other
   - Number of exits
   - Number of entrances
   - Recreational Locations
   - Vital Locations
   - Residence Locations

13. With respect to “Station Criticality”, indicate the relative importance of impacts over each other
   - Absolute (L)
   - Strong (L)
   - Moderate (L)
   - Equal
   - Strong
   - Strong

B. Main criteria comparison with respect to each other:
14. With respect to “Station Characteristics”, indicate the relative importance of impacts over each other
   - 9 = Very
   - 7 = Strong
   - 5 = Moderate
   - 3 = Equal
   - 1 = Moderate
   - 5 Very
   - 7 Strong

15. With respect to “Station Location”, indicate the relative importance of impacts over each other
   - Number of exits
   - Number of entrances
   - Recreational Locations
   - Vital Locations
   - Residence Locations

C. Sub-criteria comparison with respect to main criteria:
17. With respect to “Station Characteristics”, indicate the relative importance of impacts over each other
   - Absolute (L)
   - Strong (L)
   - Moderate (L)
   - Equal
   - Strong
   - Strong

18. With respect to “Station Location”, indicate the relative importance of impacts over each other
   - Number of exits
   - Number of entrances
   - Recreational Locations
   - Vital Locations
   - Residence Locations

21. Are there any other factors of station criticality that the survey failed to address? If yes, please indicate them.
**IMPACTS WEIGHTS**

**Criticality Index Model**

- **1. Station Characteristics (C)**
  - C1: Number of exits
  - C2: Number of Levels

- **2. Station Location (L)**
  - L1: Recreational
  - L2: Residence
  - L3: Vitalities

- **3. Station nature of use (N)**
  - N1: End Station
  - N2: Intermodal Station

The chart illustrates the global and local weights for each category, with a focus on the criticality of different station characteristics and locations.
Risk Index
Risk Index Model

- Probability of Failure
- Consequences of Failure
- Criticality Index

Fuzzy Inference Engine

- Fuzzification
  - Fuzzy Sets
  - Fuzzy Rules
  - Knowledge Base

- Defuzzification

Risk Index
Risk Index Model
Risk Index Model

R_I: IF PoF is X_i and CoF is Y_i and C_R is Z_i then Risk Index is L_i
<table>
<thead>
<tr>
<th>Organizational effects</th>
<th>CONSEQUENCES OF FAILURE</th>
<th>Critical ((0.6,1,1.4))</th>
<th>Tolerable ((0.2,0.6,0.8))</th>
<th>Negligible ((-0.4,0,0.4))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Financial</strong></td>
<td>Financial cost will be high for repair and for giving alternative (&gt;5\text{M}$)</td>
<td>Financial impact is a factor but usually the amount of money needed for this type of impact is easily absorbed during the current year or the following one (2\text{M}$-5\text{M}$)</td>
<td>financial is not an impact it’s covered by operational cost (&lt;2\text{M}$)</td>
<td></td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td>Reduction of customer satisfaction rate that causes their permanent loss</td>
<td>Reduction of customer satisfaction rate that causes temporary shifting of service</td>
<td>Customers are barely affected by service disruption</td>
<td></td>
</tr>
<tr>
<td><strong>Operational</strong></td>
<td>Failure causes a service outage affecting more than one metro line for more than 30 minutes.</td>
<td>Failure causes a service outage affecting a subway line in full or partial interchange outage affecting more than one line for a maximum of 15 min</td>
<td>Failure causing operation mode degradation for a time between 2 and 5 minutes.</td>
<td></td>
</tr>
</tbody>
</table>
## Risk Index Model

<table>
<thead>
<tr>
<th>Risk level</th>
<th>Membership function</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible</td>
<td>-0.25,0,0.25</td>
<td>No intervention required</td>
</tr>
<tr>
<td>Minor</td>
<td>0,0.25,0.5</td>
<td>Intervention required is optional, can be postponed.</td>
</tr>
<tr>
<td>Significant</td>
<td>0.25,0.5,0.75</td>
<td>Intervention is required and should be planned.</td>
</tr>
<tr>
<td>Critical</td>
<td>0.5,0.75,1</td>
<td>Obligatory intervention required, yet not urgent</td>
</tr>
<tr>
<td>Catastrophic</td>
<td>0.75,1,1.75</td>
<td>Urgent and Obligatory intervention is required</td>
</tr>
</tbody>
</table>
Model Implementation
# Case Study

<table>
<thead>
<tr>
<th></th>
<th>STA</th>
<th>TUN</th>
<th>AUX</th>
</tr>
</thead>
<tbody>
<tr>
<td>STB 1</td>
<td>0.2501</td>
<td>0.1173</td>
<td>0.0859</td>
</tr>
<tr>
<td>STB 2</td>
<td>0.0000</td>
<td>0.1800</td>
<td>0.0000</td>
</tr>
<tr>
<td>STB 3</td>
<td>0.2685</td>
<td>0.1797</td>
<td>0.0000</td>
</tr>
<tr>
<td>PoF line A</td>
<td></td>
<td></td>
<td>0.0038</td>
</tr>
<tr>
<td>STB 4</td>
<td>0.6732</td>
<td>0.1644</td>
<td>0.2257</td>
</tr>
<tr>
<td>STB 5</td>
<td>0.2243</td>
<td>0.1489</td>
<td>0.0000</td>
</tr>
<tr>
<td>PoF line B</td>
<td></td>
<td></td>
<td>0.1718</td>
</tr>
<tr>
<td>STB 6</td>
<td>0.5130</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>PoF line C</td>
<td></td>
<td></td>
<td>0.5130</td>
</tr>
</tbody>
</table>

\[ P_{\text{Segment}} = \prod_{i=1}^{3} P_{\uparrow \text{Line}i} = 0.0003 \]
Model Implementation
## Risk Report

<table>
<thead>
<tr>
<th>Station</th>
<th>STA 4</th>
<th>STA 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Probability of Failure</td>
<td>0.673</td>
<td>0.513</td>
</tr>
<tr>
<td>✓ Consequence of Failure</td>
<td>0.343</td>
<td>0.279</td>
</tr>
<tr>
<td>✓ Criticality Index</td>
<td>0.743</td>
<td>0.252</td>
</tr>
<tr>
<td>✓ Risk Index</td>
<td>0.821</td>
<td>0.5</td>
</tr>
<tr>
<td>✓ Revenue Loss ($CAD)</td>
<td>$583,779</td>
<td>$526,706</td>
</tr>
<tr>
<td>✓ Repair Cost ($CAD)</td>
<td>$225,000</td>
<td>$225,000</td>
</tr>
<tr>
<td>✓ Service continuation</td>
<td>Weekend</td>
<td>Weekend</td>
</tr>
<tr>
<td>✓ Interruption Rate</td>
<td>Total (1)</td>
<td>Total (1)</td>
</tr>
<tr>
<td>✓ Time to repair (days)</td>
<td>65</td>
<td>50</td>
</tr>
<tr>
<td>✓ User Traffic (annual)</td>
<td>1092714</td>
<td>1281651</td>
</tr>
</tbody>
</table>
RESEARCH CONTRIBUTIONS

- Develop a network level risk-based asset management model
- Study subway network @ functional and structural perspectives
- Develop Probability of failure, Consequence of Failure and Criticality models
- Integrate the three models into a comprehensive risk index model
Thank You!