Transportation Network Resiliency: The Role of Redundancy

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Outline

- Motivation and background
- Network-based redundancy measures
- Applications
  - Metro networks
  - Road networks
  - Freight networks
- Concluding remarks
- Future research
The Emergency Events Database (2008) defines a disaster as an event that fits at least one of the following criteria: 1) 10 or more people killed; 2) 100 or more people affected; 3) declaration of a state of emergency; 4) call for international assistance.

Figure 1.1: Frequency of disasters [Source: Emergency Events Database (2008)]
Disasters and Transportation Networks

**Disasters (Natural or Manmade)**

- **Natural Disaster:** Earthquake, Tsunami, Avalanche, Flood, Wildfire, Volcano
- **Structural Collapse:** Bridge, Tunnel, Overpass
- **Terrorist:** 9/11 Attack, London Tube, Riot
- **Incident:** Accidents, Road Closure, Work zone, Special events
- **Regulation, Policy:** Hazard Material Routes

**Disruption to Transportation Network and Economic Impact**

- (Thailand Mega Flood in 2011)
  Estimates of economic losses = 1,425 billion THB (~$ 45.7 billion) (World Bank, 2012)

- (Hurricane Sandy in 2012)
  Estimates of losses due to the shutdown of business activity in the East Coast = $30 billion-$50 billion (IHS Global Insight, 2013)
Resiliency is characterized by the four “Rs” concept: Robustness, Redundancy, Resourcefulness, and Rapidity (Bruneau et al., 2003).

How to make the “4Rs” concept operational with sound methodology?

Transportation Network Resiliency Framework

- **Resiliency**
  - Robustness
  - Redundancy
  - Resourcefulness
  - Rapidity

- Strategic Planning (Long Term)
- Tactical Planning (Medium Term)
- Operational Planning (Short Term)

- Pre-Event
- During
- Post-Event

- Time
- Planning
- Design

- Flexible
- Robust
- Vulnerable

- Normalcy
- Ultimate

- Acceptable Performance Gap

1. Go Back to Normalcy
2. Move to Recovery + Redesign Stage
3. Accept the Performance Gap

- Disruption/Shock
- Recovery and Redesign Planning
- Traffic Regulation
- Redundancy
- Traffic Regulation
- Recovery
- Redesign
Definitions of Redundancy

The Webster/Merriam Dictionary:
(1) Exceeding what is necessary or normal, or
(2) Serving as a duplicate for preventing failure of an entire system upon failure of a single component.

➢ Power System/Supply Engineering: Excess capacity or backup system to reduce impact of component failures
(e.g., Power failure scenario in the ER!!)

➢ Structural Engineering: the ability of a structural system to redistribute stresses to its members/connections and thereby ensuring the safety of structural systems. (Fang and Fan, 2011)

➢ Water Distribution System: the existence of alternative pathways from the source to demand nodes or excess capacity in normal operating conditions when some components of the system become unavailable (Kalungi and Tanyimboh, 2003)
Redundancy in Transport Networks

- Redundancy is an important indicator in the development of an emergency response and recovery plan (FHWA, 2006)
- Redundancy is an important concept to reduce transport network vulnerability as well as enhance resiliency during disastrous events
- There is very little research on redundancy in transport networks (no formal definition and lack of quantitative measures)
- Few researchers have concretely developed quantitative measures and computational methods to assess the multifaceted characteristics of transport network redundancy.
Network-based Redundancy Measures

Develop *two quantitative measures* for assessing transportation network redundancy:

i) Route Diversity (user perspective): How many alternative routes are there?

ii) Network Spare Capacity (planner perspective): How much spare capacity does the network have?

- Have *different characterizations* on network redundancy *from different perspectives*
- *Complement each other* by providing meaningful information to both users and planners
Measure 1: Route Diversity

- **Route diversity** characterizes the existence of *multiple routes* available for *travelers*.
Efficient routes (Dial, 1979): A route that consists of links that take network users further away from the origin and closer to the destination.

\[ l_r(\text{head}_a) > l_r(\text{tail}_a), \forall a \in \Gamma_k \]

Need some way to count number of routes for the real-world network!!
Effective Routes

- **Efficient and not-too-long route**

- **Efficient route** (Dial, 1979)

\[ l_r(\text{head}_a) > l_r(\text{tail}_a), \forall a \in \Gamma_k \]

- **Not-too-long route** (Leurent, 1997)

A shorter detoured route with an acceptable cost

\[
(1 + \tau^a_r)(l_r(\text{head}_a) - l_r(\text{tail}_a)) \geq l_a
\]

\[
\Rightarrow l_k \leq \left(1 + \tau^{\text{max}}_r\right) \min_p l_p
\]
Different Levels of Aggregation

Aggregate the degree of O-D pair connections to different levels according to planners’ different evaluation purposes.
Measure 2: Network Spare Capacity

- The route diversity is assessed using only network topology characteristics.
- Capacity is not explicitly considered in the evaluation of route alternatives.
- *Congestion effect* and *travelers’ choice behavior* are two critical characteristics of transportation systems.

Network-wide capacity is not just a simple sum of the individual link capacities.
Measure 2: Network Spare Capacity

- **Spare (Reserve) Capacity Model**
  (originally proposed by Wong and Yang, 1997)

Existing Demand \( (q) \)

100% Capacity

Reserve Capacity

Finding the network reserve capacity multiplier \( \mu \) using bi-level programming:

- **Upper level**: Maximize Multiplier \( \mu \)
- **Lower level**: Traffic Assignment Problem

\[
\text{Capacity Multiplier of Existing Demand} = 100(\mu - 1)\%
\]
Network Spare Capacity

\[ \max \mu, \]

s.t.

\[ v_a(\mu q) \leq \theta_a C_a, \ \forall a \in A, \]

where \( v_a(\mu q) \) is obtained by solving the lower-level UE problem under a given \( \mu \):

\[ \min_{v(\mu q)} \sum_{a \in A} \int_{0}^{v_a} t_a(w)dw, \]

s.t.

\[ \sum_{k \in K_{rs}} f_{rs}^k = \mu \cdot q_{rs}, \ \forall r \in R, s \in S, \]

\[ v_a = \sum_{r \in R} \sum_{s \in S} \sum_{k \in K_{rs}} f_{rs}^k \delta_{ak}, \ \forall a \in A, \]

\[ f_{rs}^k \geq 0, \ \forall k \in K_{rs}, r \in R, s \in S, \]

Maximize Capacity Multiplier

Link Capacity Constraints

User Equilibrium (UE) Behavior
Metro Networks

Motivation

- Metro is a key mode in many metropolitan cities.
- In Hong Kong, metro takes up more than 40% (or about 5 million) daily trips.
- In China, metro networks have been growing very rapidly, starting with three cities (Beijing, Shanghai, and Guangzhou) with five lines in 2000 to twenty two cities with eighty-eight metro lines by 2014.
- As of 2016, twenty six Chinese cities have metro systems and thirty nine more have metro systems approved according to the National Development and Reform Commission.
- Most stations and tracks in metro networks are irreplaceable for daily operations. If one or more stations break down by incidents, it will have a great impact not only on this metro line but also on the whole metro network.
Incidents at Metro Stations

Collapse

Leak

Terrorist attack

Fire
### Some Metro Incidents in the Past Decade

<table>
<thead>
<tr>
<th>Location</th>
<th>Time</th>
<th>Incident type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>London Underground (UK)</td>
<td>July 2005</td>
<td>Terrorist attack</td>
<td>British Red Cross</td>
</tr>
<tr>
<td>Beijing Metro (China)</td>
<td>June 2006</td>
<td>Collapse</td>
<td>Sina</td>
</tr>
<tr>
<td>Hangzhou Metro (China)</td>
<td>Nov. 2008</td>
<td>Collapse</td>
<td>Xinhua Online</td>
</tr>
<tr>
<td>Beijing Metro (China)</td>
<td>Feb. 2010</td>
<td>Leak</td>
<td>Sohu</td>
</tr>
<tr>
<td>Moscow Metro (Russia)</td>
<td>Mar. 2010</td>
<td>Suicide bomber</td>
<td>CNN World</td>
</tr>
<tr>
<td>Beijing Metro (China)</td>
<td>Jan. 2013</td>
<td>Collapse</td>
<td>China Daily</td>
</tr>
<tr>
<td>Nanjing Metro (China)</td>
<td>Nov. 2013</td>
<td>Collapse</td>
<td>People's Daily Online</td>
</tr>
<tr>
<td>Cairo Metro (Egypt)</td>
<td>June 2014</td>
<td>Terrorist attack</td>
<td>The Wall Street Journal</td>
</tr>
<tr>
<td>Mumbai Metro (India)</td>
<td>July 2014</td>
<td>Leak</td>
<td>Dnaindia</td>
</tr>
<tr>
<td>Zhengzhou Metro (China)</td>
<td>Sept. 2014</td>
<td>Leak</td>
<td>China Daily</td>
</tr>
</tbody>
</table>
Use Route Diversity to Address Two Questions for Metro Networks

- How many *reasonable routes* are there for passengers between any two stations in normal operations or in the event of a disruption?

- Which stations are *most vulnerable* (i.e., have the largest impacts to the overall metro network when they are disrupted)?
Solution Procedure

Three main steps: (1) reasonable adjacent matrix, (2) number of reasonable routes for each OD pair, and (3) route diversity index.

1. Obtain the reasonable matrix \( u_r \) for the origin \( r \).
   - Set \( r = 1 \) and \( u_r = u \)
   - Set \( a = 1 \)
   - Calculate the shortest route costs \( f_{\text{min}}(r, a_0) \) and \( f_{\text{max}}(r, a_0) \)
   - If \( f_{\text{min}}(r, a_0) \leq f_{\text{max}}(r, a_0) \) then:
     - Set \( u_r(a_0, a_0) = 0 \)
   - else:
     - Set \( a < |r| \)
     - Set \( a = a + 1 \)

2. Calculate the number of reasonable routes \( x(r, a) \) between the OD pair \((r, a)\).
   - Set \( m = m + 1 \)
   - Set \( n = n + 1 \)
   - Set \( j = j + 1 \)
   - Set \( n = n + 1 \)
   - Set \( m = m + 1 \)
   - Set \( j = j + 1 \)
   - Set \( n = n + 1 \)
   - Set \( m = m + 1 \)
   - Set \( j = j + 1 \)
   - Set \( n = n + 1 \)
   - Set \( m = m + 1 \)
   - Set \( j = j + 1 \)
   - Set \( n = n + 1 \)
   - Set \( m = m + 1 \)
   - Set \( j = j + 1 \)
   - For each \( 1 \leq n \leq |r| \), set \( x(r, n) = u_r(j, n) \)

3. Calculate the route diversity index.
   - Calculate the route diversity index \( R \) by equation (3.2)
   - End
Case Study - Beijing Metro

Beijing Metro Network (Oct. 2014)

- 233 stations
- 526 links
- 54,056 OD pairs

Source: Beijing Mass Transit Railway Operation Corporation Limited.
Simplified Beijing Metro

Simplified Beijing Metro Network

- 61 zones
- 38 transfer stations
- 99 nodes
- 254 links
- 9702 OD pairs
Reasonable Routes

Minimum = 1  Average = 2.2574
Maximum = 43  Probability [1] = 57.57%
Vulnerable Stations

Value of routes diversity with all stations in normal operation

1. Xizhimen 西直门        2. Chegongzhuang 车公庄 
3. Xidan  西单                 4. Zhicunlu 知春路         
5. Fuxingmen 复兴门     ...          10. Guloudajie 鼓楼大街

Disrupted station index

Value of routes diversity

1. Xizhimen 西直门        2. Chegongzhuang 车公庄 
3. Xidan 西单                 4. Zhicunlu 知春路         
5. Fuxingmen 复兴门     ...          10. Guloudajie 鼓楼大街

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1. Xizhimen 西直门        2. Chegongzhuang 车公庄 
3. Xidan 西单                 4. Zhicunlu 知春路         
5. Fuxingmen 复兴门     ...          10. Guloudajie 鼓楼大街
Top Ten Vulnerable Stations

1. Xizhimen 西直门
2. Chegongzhuang 车公庄
3. Xidan 西单
4. Zhicunlu 知春路
5. Fuxingmen 复兴门
6. Pinganli 平安里
7. Xuanwumen 宣武门
8. Dazhongsi 大钟寺
9. Dongdan 东单
10. Guloudajie 鼓楼大街
Value of route diversity index with the top ten critical stations disrupted one at a time and in comparison with all stations in normal operation.

<table>
<thead>
<tr>
<th>Station</th>
<th>Xizhimen</th>
<th>Chegongzhuang</th>
<th>Xidan</th>
<th>Zhicunlu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route diversity</td>
<td>1.4281</td>
<td>1.6066</td>
<td>1.6569</td>
<td>1.6654</td>
</tr>
<tr>
<td>Comparison</td>
<td>-36.74%</td>
<td>-28.28%</td>
<td>-26.60%</td>
<td>-26.22%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station</th>
<th>Fuxingmen</th>
<th>Pinganli</th>
<th>Xuanwumen</th>
<th>Dazhongsli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route diversity</td>
<td>1.7733</td>
<td>1.7808</td>
<td>1.8036</td>
<td>1.8181</td>
</tr>
<tr>
<td>Comparison</td>
<td>-21.45%</td>
<td>-21.11%</td>
<td>-20.11%</td>
<td>-19.46%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Station</th>
<th>Dongdan</th>
<th>Guloudajie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route diversity</td>
<td>1.8661</td>
<td>1.8825</td>
</tr>
<tr>
<td>Comparison</td>
<td>-17.33%</td>
<td>-16.61%</td>
</tr>
</tbody>
</table>
Other Metro Networks

- **Shanghai Metro**
  - Number of lines: 14
  - Number of stations: 303

- **Beijing Metro**
  - Number of lines: 17
  - Number of stations: 290

- **Guangzhou Metro**
  - Number of lines: 10
  - Number of stations: 166

- **Hong Kong Metro**
  - Number of lines: 11
  - Number of stations: 93

- **London Metro**
  - Number of lines: 13
  - Number of stations: 385

- **Tokyo Metro**
  - Number of lines: 16
  - Number of stations: 266
Road Networks
Example 1: Small Network

To demonstrate why it is necessary to have two measures for systematically characterizing the transportation network redundancy

Demand of O-D (1, 3), (1, 4), (2, 3) and (2, 4) are 40, 10, 10, and 50

Scenario 0: the current network (base case)
Scenario 1: construct a new road from node 1 to node 2 ($t_a^0=4$, $C_a=80$)
Scenario 2: expand the capacity of link 5 by 50%
Scenario 3: construct a new road from node 1 to node 6 ($t_a^0=6$, $C_a=80$)
Scenario 4: construct a new road from node 2 to node 6 ($t_a^0=6$, $C_a=80$)
• Under different network reconfiguration or enhancement schemes, using either route diversity or network spare capacity SOLELY may not be able to capture the full picture of network redundancy

• They can complement each other for a two-dimensional network redundancy characterization
Example 2: Winnipeg Network in Canada

- To demonstrate applicability of computational methods

- Winnipeg network:
  - 154 zones
  - 1,067 nodes
  - 2,535 links
  - 4,345 O-D pairs
Travel Alternative Diversity: Effective versus Efficient Routes

Effective routes: efficient and not-too-long

Efficient routes

Min=1; Max=634; Mean=11.63; Median=4; Pro[1, 5]=62.55%; Pro[1, 10]=78.18%

Min=1; Max=16424; Mean=149.77; Median=12; Pro[1, 5]=33.76%; Pro[1, 10]=48.84%
Network Spare Capacity

\[ \max \mu \]
\[ \text{s.t. } v_a(\mu) \leq \theta_a C_a, \quad \forall a \]
Freight Networks
Redundancy: Bi-modal Network Spare Capacity

Reserve (Spare) Capacity for Bi-modal Transportation Networks

- Consider capacity of bi-modal freight transportation networks (i.e., truck-rail)
- Consider capacity of freight operations at origin and destination nodes
Multimodal Capacity Constraints

Origins (Production)
- Loading Facility
  - Resources (i.e., time, labor)
  - Technological Feasibility
  - Safety operation
  - Inventory Capacity

Modal Capacity
- Capacity of link/corridor (i.e., LOS E)
- Operation (e.g., signalization, siding for train)
- Restriction and Regulation (e.g., truck restriction)
- Performance of vehicle (e.g., train speed, locomotive power)

Link/Route/Corridor Capacity

Destinations (Consumption)
- Unloading Facility
  - Resources (i.e., time, labor)
  - Technological Feasibility
  - Safety operation
  - Warehouse or Drayage Capacity

Nodal Capacity
Conversion factors for coal truck-rail transportation

1 Coal Train
(112 wagons per train, 110 tons /wagon)

\[ H_{rs, \text{max}}^{\text{rail}} = \frac{A_c}{B} \times \left(\frac{100}{L}\right), \]

\[ A_c = 0.031L\sqrt{\frac{1}{S}} \left(\frac{M \times 150}{L} - \frac{150}{S - I - 1.846}\right), \]

(for a single track)

\[ A_c = \frac{-\left(67.276P + 151.708D\right)}{L} + \frac{\left(67.276P + 151.708D\right)^2}{L^2} - \frac{L^2}{(3,892,500S/L)^2} \times \left(1.41432 - \frac{150M}{L + 150} + \frac{S + I}{S}\right) \]

\[ \frac{1,946,250S}{1,946,250S} \]

(for a double track)

287 Coal Trucks (43 tons /truck)

Variables

\(A_c\) is the average delay per train at capacity (hours) for a single track railroad or double-track railroad,

\(B\) is the delay slope,

\(L\) is the length of line (mile),

\(M\) is the maximum allowable total running time (i.e., operation hours at terminal),

\(S\) is the speed of the slowest class of through freight train (miles/hour),

\(P\) is the dispatch peaking factor (trains per peak hour),

\(D\) is a directional factor, and

\(I\) is the amount of imposed delays on regular freight trains (e.g., required stops).
Network Spare Capacity (Bi-modal network)

Upper-Level Problem: Maximize network capacity multiplier

Maximize Network Capacity Multiplier

s.t.

Link capacity (truck)
Link capacity (rail)
Capacity at origin (truck + rail)
Capacity at destination (truck + rail)
Non-negativity constraints

s.t.

Lower-Level Problem: Bi-modal User Equilibrium Traffic Assignment

User Equilibrium of Bi-modal network

s.t.

Scaled-up total O-D demand
Demand conservation constraints
Conservation constraints of truck path flows
Definitional constraints of truck link flows
Non-negativity constraints of truck path flows
Non-negativity constraints of total O-D demand
Network Spare Capacity: Ultimate Capacity

**Network Spare Capacity (Truck-Rail Network: Bi-modal networks)**

**Upper-Level Problem:** Maximize O-D throughputs

- Maximize O-D throughputs
- Link capacity (truck)
- Link capacity (rail)
- Capacity at origin (truck + rail)
- Capacity at destination (truck + rail)
- Non-negativity constraints

**Lower-Level Problem:** Bi-modal User Equilibrium Traffic Assignment

- Demand conservation constraints
- Definitional constraints of truck path flow
- Definitional constraints of truck link flows
- Non-negativity constraints of truck path flows
- Non-negativity constraints of total O-D demand
Bi-modal Transportation Network:
Coal Transportation Network

In Utah, Coals are transported by two major modes: **Truck (42%) and Rail (58%)**
Coal Production: **80,000 Tons/Day** from 7 Major Coal Mines divided into 3 Groups in Southern Utah
Efficient Routes of Bi-modal Network

a) Efficient routes from mine group 1

b) Efficient routes from mine group 2

c) Efficient routes from mine group 3

d) Potential bottlenecks (top 5 links)
Bi-modal Network Spare Capacity

Current Multimodal Networks

- Current Demand = 84.4 KTon/day
- Reserved Capacity = 145.0 KTon/day
- Ultimate Capacity = 421.4 KTon/day

Effect of Railroad Project

Multimodal Networks with Proposed Railroad

- Current Demand = 84.4 KTon/day
- Reserved Capacity = 146.0 KTon/day
- Ultimate Capacity = 610.8 KTon/day

μ=1.73

a) current bimodal network  
b) bimodal network with the proposed railroad

Capacity increases due to proposed railroad projects  
(Mine Group 1-> Levan)
Concluding Remarks

- Network-based measures for systematically characterizing transport network redundancy
  - Route diversity
  - Network spare capacity
- Have different characterizations on network redundancy from different perspectives
- Complement each other by providing meaningful information to both users and planners
- Apply to three transport networks: Metro, highway, and freight
Limitations and Future Research

- Current redundancy measure for metro networks only considers route diversity; need to estimate the metro network capacity.
- Current method considers individual networks, single mode or bimodal; need to integrate multiple networks and multiple modes into an integrated network redundancy evaluation procedure.
- Make use of these network-based redundancy measures to develop redundant network design model.
- How to make the “4Rs” concept operational with sound methodology.
Questions & Answers