Research on Conceptual and Analytic Model of Vulnerability of Transportation Network

Zhiyun Zou
Huazhong Univ. of Sci. & Tech., China
Xin (Alyx) YU (Presenter)
Univ. of Hawaii at Manoa
OUTLINE

• INTRODUCTION
• TRANSPORTATION NETWORK VULNERABILITY
• MACRO CONCEPTUAL MODEL
• MICRO VULNERABILITY ANALYTIC MODEL
• CONCLUSION
INTRODUCTION

• An economically and long-term sustainable transportation network

• What’s Perfect transportation network?
  “not only that these links exist between different destinations, but also that it is open to traffic, environment or other natural incidents” (Berdica 2002)

• Affects:
  - Bad weather
  - Traffic accident
  - Emergency
- Sensitive to the status of surrounding, neighboring communities and social economics
- Not taken into consideration in urban transportation planning
- Predictable or unpredictable
- Spread fast from one area to another
• Concept of Vulnerability
Susceptibility to incidents that can result in considerable reductions in the transportation network serviceability

• Concept of Serviceability
The possibility or risk to use that network during a giving time period

• Basic theory
Adopted the reliability theory and Analytic Hierarchy Process (AHP) to evaluate the probability for an event of negative impact to transportation network
TRANSPORTATION NETWORK VULNERABILITY

• Characteristics of Transportation network vulnerability

1. A series of incidents are possible to occur. These events may lead to unpredictable change of traffic demand and supply
2. Unstable and interactive with other external systems
3. Damages on transportation network are difficult to be recovered in a short term
4. A incident affecting the transportation network may trigger other negative incidents
• Transportation network vulnerability depends on 3 factors
  1. System stability and reliability
  2. The extent of damage
  3. The ability of network recovery

• The occurrence of the incidents and consequent impacts on transportation network is of randomness
  1. Randomness of traffic demand
  2. Randomness of traffic supply
  3. Randomness of trip behavior
Transportation Network Vulnerability

Serviceability
Susceptibility
Connectivity

Incidents

Transportation Network

Supply Randomness

Demand Randomness

Vulnerability Risk

Counteractive Ability
Operating Status
Network Recovery ability

Transportation Network Vulnerability

TRANSPORTATION NETWORK VULNERABILITY
MACRO CONCEPTUAL MODEL

• Evaluation Indices System
A tri-layered evaluation index system
1. First layer is the road network topology
2. Second layer is the network operating status
3. Third layer is the traffic emergency management system
• Layer 1: Road network topology
Indices
1. Network connectivity (*Network density*, *Connectivity*, *Stability*)
2. Network serviceability (*Serviceability degree*, *LOS*)
3. Carrying volume of network (*Capacity*, *Impedance*)
• Layer 2: Network operating status

Indices

1. Intersection congestion rate of principal arterials
2. Intersection congestion rate of minor arterials
3. Mileage congestion rate of principal arterials
4. Mileage congestion rate of minor arterials

Traffic volume, Density, Travel time, Occupancy, vehicle delay
Layer 3: Traffic emergency management system

Indices

1. Detectability of traffic incidents (Detection rate, Rate of mistaken detection, Mean time of incident detection)
2. Respondence to traffic emergency (Time of making countermeasures)
3. Level of services of emergency facilities (Countermeasure performance)
MICRO VULNERABILITY ANALYTIC MODEL

• Based on the evaluation of transportation network unreliability, operating status, and ability of network recovery

1. Vulnerability degree of individual units
2. Vulnerability Degree of Transportation Network System
• Vulnerability degree of individual units

1. Connectivity unreliability of individual units
(The impossibility of traveling directly from a node to another one)

The probability (P) of connectivity unreliability:

\[ P = k \times f \left( \frac{v}{c} \right) \]

k = compensation factor
V/C = saturation rate

\[ f \left( \frac{v}{c} \right) = \begin{cases} 
\frac{(v/c)^2}{2(1 - \beta)} & (0 \leq v/c \leq \beta) \\
-\frac{(v/c - 1)^2}{2\beta^2} + 1 & (\beta \leq v/c \leq 1) \\
1 & (1 \leq v/c)
\end{cases} \]

\[ \beta = \text{Saturation constraint} \]
2. Operating status of individual units

- The congestion rate of an individual unit (PB) is used as a parameter
- PB measured by averaging the congestion rate of the intersections of both ends (PBI1 and PBI2) of each link unit
- The link units are defined as basic individual units

\[
PB = \frac{1}{2}(PBI_{1} + PBI_{2})
\]

PB = Probability of the approaching traffic volume over the capacity of intersection during peak periods

If delay over 60s/veh (excluding signal time), the intersection was assumed to be congested
3. Ability of Network Recovery
Assumed the event-response process consists of:
1. incident detection \((t_d)\)
2. incident analysis \((t_a)\)
3. countermeasures-making \((t_m)\)
4. and implementation \((t_i)\)

The time spending in the entire process of response (event-response time \(t_R\))

\[ t_R = t_d + t_a + t_m + t_i \]

*If the response time is less than 3 minutes, the negative impacts of event-response time on transportation network can be ignored*
• Combine the above three factors

The analytic model of individual unit vulnerability degree (G) :

\[ G = PB \times \exp(w_1 0.1 t_R - 1) + w_2 P) \]

\[ = \frac{1}{2} (PBI_1 + PBI_2) \times \exp\left( w_1 (0.1(t_d + t_a + t_m + t_i) - 1) + w_2 kf \left( \frac{v}{c} \right) \right) \]

\[ w_1, w_2, k = \text{compensation factor} \]
Vulnerability Degree of Transportation Network System

- Based Paths \( R_1, R_2, \ldots, R_r, \ldots, R_n \) connecting an OD pair \((i, j)\)
- The vulnerability degree of based route \( R_r \) is \( G_{ijr} \)
- The \( R_r \) route consists of \( m \) link units
  \( l_{r1}, l_{r2}, \ldots, l_{rk}, \ldots, l_{rm} \)
- The length of link unit \( l_{rk} \) is \( l_{rk} \) and the vulnerability degree of link unit \( l_{rk} \) is \( G_{ijrk} \)

MICRO VULNERABILITY ANALYTIC MODEL
• The vulnerability degree of based path “Rr”

\[ G_{ijr} = \frac{\sum_{k=1}^{m} (l_{er_k} \times G_{ijrk})}{\sum_{k=1}^{m} l_{er_k}} \]

• The vulnerability degree of an OD pair “Gij”

\[ G_{ij} = \frac{\sum_{r=1}^{n} (f_{r}^{ij} \times G_{ijr})}{D_{ij}} \]

\[ f_{r}^{ij} = \text{the carrying traffic volume of based path } R_r \text{ between OD pair } (i,j) \]

\[ D_{ij} = \text{the traffic demand between OD pair } (i,j) \]
• Whole network

Assume that the transportation network has “n” OD pairs

Vulnerability degree of the transportation network system “$G_s$”

$$G_s = \sum_{q=1}^{m} \xi_q G_q$$

$G_q$ = the vulnerability degree of the $q^{th}$ OD pair

$\xi_q$ = the weight value of the $q^{th}$ OD pair in the system, and

$$\sum_{q=1}^{m} \xi_q = 1$$
CONCLUSION

• Quantify the vulnerability of transportation network
• Assess three essential impact factors of transportation network
• Indices system of transportation network vulnerability was established

• Analytic model of vulnerability is immature
• Critical factors were ignored and simplified
• No evaluation standard
THANK YOU AND ???

Zhiyun Zou

cj8601@163.com
(86)138 0865 6659
Department of Civil Engineering, Huazhong University of Science and Technology, Wuhan, China, 430074

Xin (Alyx) YU
xinyu@hawaii.edu
University of Hawaii at Manoa
Department of Civil and Environmental Engineering
Traffic and Transportation Laboratory