Influence of Route Choice Behavior on Vulnerability to Cascading Failure in Transportation Networks

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Transport Vulnerability

- Transportation network: one of critical infrastructures supporting the movement of people and goods
- Catastrophic events sometimes occur in transport networks
- **Transport network vulnerability** has been studied intensively in recent years

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**Risk Curve**

from Mattson and Jenelius (2015)
Cascading Failure in Complex Networks

- Network vulnerability has also been studied in complex networks.
- One topic is cascading failure mainly discussing following phenomena (Barabasi, 2016):
  1. Normal State
  2. Initial Failure
  3. Propagation of Failures
  4. Ultimate State

Diagram:
- Blackout
- Communication Disturbance
- Financial Crisis

A *small* failure “Trigger”

Domino Effect

Catastrophic Damage
A large number of studies on network vulnerability have been published in the two fields.

How have these two fields evolved over time?

How have these two fields influenced each other?
Citation Network Analysis

1. Data Collection from Web of Science
2. Construction of a Citation Network
3. Extraction of Giant Component
4. Community Detection
5. Main Path Analysis in Each Community
6. Citation Pattern Analysis

Network Vulnerability

Relations between Communities
Community Structure in Citation Network

- Community structure of citation network has been identified

Citation Network consisting of Vulnerability Studies

Paper in Preparation
Sugishita K. and Asakura Y., Citation Network Analysis of Vulnerability Studies in the Fields of Transportation and Complex Networks.
Citation Pattern Analysis

Interdependent Networks: 1,088  'Interdependent Networks': 1,096

Transport Vulnerability: 1,453  'Transport Vulnerability': 1,362

Topological Vulnerability: 580  'Topological Vulnerability': 894

Cascading Failure: 876  'Cascading Failure': 785

Metro and Shipping: 336  'Metro and Shipping': 259

Resilience: 242  'Resilience': 181

Scattered Community: 9  'Scattered Community': 7

Little Knowledge Flow
Gridlock as Cascading Failure

Cascading Failure in Complex Networks

Blackout  Communication Disturbance  Financial Crisis

Similar phenomenon occurs in Transportation Networks… Gridlock

- Gridlock: Traffic completely standstills with zero/minimal flow (Mahmassani et al., 2013)
- Gridlock seldom occurs, but it brings about catastrophic damage
Research Objectives

• This study aims
  1. To analyze gridlock in transportation networks from the perspective of cascading failure in complex networks
  2. To investigate influences of route choice behavior on vulnerability to cascading failure
Differences in Models

◆ Assumptions in many studies about cascading failure in complex networks
  • Flow is simply assigned on the shortest paths
  • Flow is extremely fast (like electrical flow)
  • Failures sweep over instantaneously and system suddenly collapses

◆ Assumptions in this study about gridlock in transportation networks
  • Flow is based on the travelers’ route choice behavior (distinctive property in transportation networks)
  • Flow is relatively slow (propagation of shockwaves)
Cell Transmission Model (CTM)

- In order to consider properties of traffic flow, Cell Transmission Model (Daganzo, 1994; 1995) is utilized.
- CTM captures dynamic traffic phenomena such as queue formation, shockwave propagation.
- Time is discretized.
- A network is represented as cells.

\[
n_i(t + 1) = n_i(t) + y_i(t) - y_{i+1}(t)
\]

\[
y_i(t) \quad y_{i+1}(t)
\]

- Time step \( t \)
- Cell \( i - 1 \) \rightarrow Cell \( i \) \rightarrow Cell \( i + 1 \)
- Time step \( t + 1 \)
- Time Step
Route Choice Behavior

- Following rules are satisfied for travelers’ route choice behavior
  - a traveler who departs at time $t$ can obtain information about travel time of all routes calculated by the network state at $t-1$
  - a traveler never change the route after departure

- Travelers choose their routes based on logit model

$$p_{ks}^{rs}(t) = \frac{\exp(-\theta T_{ks}^{rs}(t-1))}{\sum_{i \in P_{rs}(t)} \exp(-\theta T_{is}^{rs}(t-1))}$$

- $p_{ks}^{rs}(t)$: the choice probability of the $k$th route in the set of routes from $r$ to $s$
- $\theta$: the scale parameter
- $T_{ks}^{rs}(t)$: the travel time of the $k$th route from $r$ to $s$ at time $t$
- $P_{rs}(t)$: the set of all routes from $r$ to $s$ at time $t$
Performance Index

- We assess network throughput as the performance index

\[ F(t) = \sum_{i \in C_{sink}} y_i(t) \]

- \( F(t) \): the network throughput representing the amount of flow completing travel and exiting from the network in the time interval between \( t \) and \( t + 1 \)
- \( y_i(t) \): the inflow to cell \( i \) in the time interval between \( t \) and \( t + 1 \)
- \( C_{sink} \): the set of all sink cells
Networks and Directed Cycles

• Investigate influences of route choice behavior in two networks
• Topology is slightly different
  - Network A has one directed cycle
  - Network B has two directed cycles (small and large)

\[
\begin{align*}
\text{Network A} & \quad 1 - m & 1 - m & \quad m \\
& \quad m & m & \quad 1 - m \quad 1 - m & \quad 1 - m \\
& & & & & \\
\text{Network B} & \quad 1 - m & 1 - m & \quad m & m & \quad q_{BN} & \quad m \\
& \quad m & m & \quad q_{BN} & \quad m & m & \quad 1 - m \\
\end{align*}
\]

\( m \): Merging Ratio

Temporal Capacity Reduction
Gridlock as Cascading Failure

- Gridlock can be captured as cascading failure

Network A

1. Normal State
2. Local Failure
3. Propagation of Failures
4. Ultimate state (gridlock)
Influence of Route Choice Behavior

- Results indicate that route choice behavior with high sensitivity may help to avoid gridlock naturally.

Network A

Scale parameter $\theta = 0.001$ (less sensitive)

Scale parameter $\theta = 0.01$ (more sensitive)
Influence of Route Choice Behavior

- However, gridlock state can be reached much faster due to sensitive route choice behavior

![Network B Diagram]

Scale parameter $\theta = 0.0$ (less sensitive)  
Scale parameter $\theta = 1.0$ (more sensitive)
Conclusions

- **Citation network analysis** on vulnerability studies
  - Citation network consists of vulnerability studies in the fields of transportation and complex networks
  - **Community structure** is identified
  - **Citation pattern analysis** revealed that **little knowledge flow** between transport vulnerability and cascading failure

- **Gridlock from perspective of cascading failure**
  - Gridlock can be captured as cascading failure: 1) normal state, 2) small failure, 3) propagation of failures, and 4) ultimate state
  - **Route choice behavior** sometimes helps to avoid gridlock naturally, but at other times it worsens the situation toward gridlock much faster
  - In transportation networks, critical points can be identified as directed cycles with overloaded demand
References


Thank you very much!