Resilience of Intermodal Transportation Infrastructure under Multiple Hazards

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Research Focus and Topics of Interest

**Structural reliability and natural hazard risk mitigation**

- Key emphases in the areas of
  - Portfolio structural vulnerability analysis and protection
  - Multi-hazard assessment (earthquake, surge, wave, aging...)
  - Sustainability and resilience quantification

- Application to transportation and energy/industrial infrastructure
Our Group at Rice University
Figure 1. Dominant hazard per region based on infrastructure exposure (Koks et al. 2019)

Increasing Hazard Exposures and Losses

Billion-Dollar Disaster Event Types by Year (CPI-Adjusted)

- Winter Storm
- Wildfire
- Trop Cycl
- Severe Storm
- Freeze
- Flooding
- Drought

Cost w/ 95% CI
5-Year Mean

Global Population Exposure
- Year-1975
- Year-2015

Global Built Environment Exposure
- Year-1975
- Year-2015

(Source: NOAA 2019)

(Adapted from Pesaresi et al. 2017)
Transportation infrastructure resilience is crucial during/after hazard events.

Hurricane Harvey (2017)

Gori et al. (2019)
• Impact of multiple hazards on transportation infrastructure
• Importance and complexity of modeling intermodal transportation systems
• Potential to disrupt goods flow
1. Transportation infrastructure resilience framework
2. Key input models
3. Application examples
4. Conclusions, challenges and opportunities
Definitions of Resilience

The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. (National Academy of Science, 2012)

Figure 1. Example resilience characterization drawing from state-of-art review (Gasser et al. 2019)

Gasser et al. (2019) "A review on resilience assessment of energy systems" Sustainable and Resilient Infrastructure. doi.org/10.1080/23789689.2019.1610600
Intermodal Resilience Analysis Framework

Hazard model → IM at key locations → Infrastructure inventory data

Input fragility models → Highway network component damage → Network functionality $Q(t)$

Input restoration models → Highway network component functionality

Recovery scheduling model → Network functionality $Q(t)$

for $t = t_0$ to $t_r$

Resilience index $R(t_r)$
Key input: *Hazard models*

- Hazard occurrence characterization and spatial hazard intensity modeling
  - Physics based
  - Surrogate model
  - Single / multi-hazard

Flood (Gori et al. 2019)

Earthquake (Vishnu et al. 2018)

Hurricane (Dawson et al. 2017)
Key input: *Exposure models*

- Provide information (e.g., location, structural type, and replacement cost) of the spatially distributed structures

Balomenos et al. (2019)  
Gori et al. (2019)  
Vishnu (2018)
Key input: *Fragility models*

- Provide probability of exceeding a certain limit state for the structures given the hazard intensities
  - Surrogate demand modeling
  - Limit state capacity characterization
  - Fragility curves/Parameterized fragility function

\[
P(\text{Failure}|\text{IM}, X) = \frac{1}{1 + \exp(-l(\text{IM}, X))}
\]

Logit function
Key input: Fragility models

- Railway bridge fragility (Misra & Padgett, 2019)
- Parameterized highway bridge fragility (Kameshwar & Padgett, 2014)
- Time-dependent bridge fragility (Ghosh & Padgett, 2010)
- Roadway fragility (Gidaris et al., 2019)
- Piers and wharfs at ports (Balomenos and Padgett, 2019)
**Key input: Restoration models**

- Quantify temporal functionality and restoration of structures & systems

<table>
<thead>
<tr>
<th>Description</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality model</td>
<td>Padgett &amp; DesRoches. (2007)</td>
</tr>
<tr>
<td>Restoration model</td>
<td>HAZUS (2011)</td>
</tr>
<tr>
<td>Restoration model</td>
<td>Bocchini et al. (2012)</td>
</tr>
<tr>
<td>Restoration model</td>
<td>Kameshwar et al. (2019)</td>
</tr>
</tbody>
</table>
Key input: *Recovery Scheduling and Network Analysis*

- Heuristic or optimal deployment of repair crews and recovery resources across networks

Bernier et al. (2019)

Misra and Padgett (2019)
Seismic Resilience Modeling of Rail-Truck Intermodal Transportation Networks

- Memphis Metropolitan Statistical Area (MMSA)

Misra, S., Padgett, J. E. (2019). Seismic Resilience of a Rail-Truck Intermodal Freight Network. 13th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP13), Seoul, South Korea
Intermodal Resilience Analysis Framework

Hazard model → IM at key locations → Infrastructure inventory data

Input fragility models → Highway network component damage → Intermodal terminal damage → Railway network component damage

Input restoration models → Highway network component functionality → Intermodal terminal component functionality → Railway network component functionality

Recovery scheduling model → Network functionality Q(t)

Network topological data

Freight demand data

Resilience index R(t_r) for t = t_0 to t_r

Key:
- Model
- Data
- Analysis
Parameterized Fragility Method

For each realization $i$

Bridge component $k$ and damage state $j$

Estimate response $Z_k$

Yes

$Y_{kj} = 1$

No

$Y_{kj} = 0$

$Y_{jk} = 1$

Component-level binary survive-failure vector $Y_{kj}$

Train elastic nets regularized logistic regression to predict failure

System-level binary survive-failure vector $Y_{j}^{sys}$

Train elastic nets regularized logistic regression to predict failure

Component fragility

System fragility

Restoration Informed by Empirical and Survey Data

• Online surveys of experts in post-hazard repair and restoration of roads, railway tracks and bridges were carried out.

• Goals of the surveys – harvest data relating various damage levels (component damage for bridges) to **closure decisions** (both complete and partial) and their **durations**.

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Models for closure decision

- **Decision trees** are leveraged
- Simple, interpretable, reasonable predictive capability

Models for closure duration

- **Clustered random forests** are leveraged
- Random forests – ensemble of decision trees
- Data divided into clusters – separate model fit to each cluster
- Reduces variance of predicted durations
A schematic fault tree model is proposed to illustrate the functional dependencies between the components and subcomponents of the intermodal terminal.

- An AND connector indicates that all the subcomponents listed under the gate (children) must fail for the parent node to fail.

- OR connector indicates that the parent fails if any one of the children fail.

- Restoration models of each subcomponent obtained from HAZUS-MH (FEMA 2015)
Integrated Multi-scale Intermodal Network

Layers of intermodal network

Adjacency matrix
Minimize \( \alpha \times O_1 + (1 - \alpha) \times (O_2 + O_3 + O_4) \)

- \( O_1 \) = Cost of repair
- \( O_2 \) = Cost of freight transport
- \( O_3 \) = Cost of unmet demands
- \( O_4 \) = Cost of excess supply

**Key Decision Variables**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta y_{bt} )</td>
<td>Binary variable stating if crews are assigned to component ( b ) at time ( t )</td>
</tr>
<tr>
<td>( y_{bt} )</td>
<td>Functionality of component ( b ) at time ( t )</td>
</tr>
<tr>
<td>( x_{ijtk} )</td>
<td>Freight containers on link ( ij ) at time ( t ) carrying shipment ( k )</td>
</tr>
</tbody>
</table>

Subject to

- Flow conservation constraints
- Constraints relating functionality with repair actions
- Constraints relating component closure status to functionality
- Link capacity constraints
- Resource constraints

Collaboration with Andres Gonzalez (OSU)
Testbed Regional Intermodal Network

- Testbed regional intermodal network: Memphis, TN
- 5 Class I railroads operate in the region (BNSF, CN, CSXT, NS and UP)
- Hub of freight traffic
  - 153 highway bridges
  - 202 railway bridges
  - 6 intermodal terminals
- Scenario earthquake
  - Magnitude 7.7
  - Point source at [35.3°N, 90.3°W]
Evaluation of Network Component Functionality

- Bridges – probability of closure
- Roadways and railway tracks – probability of closure
- Intermodal terminals – probability of failure

- Monte Carlo Simulation of intermodal network with randomly assigned restoration
- Initial loss of network functionality is dictated by intermodal terminals
- Long term loss of network functionality is dictated by bridges
• Network performance over time

Figure 1. Example intermodal performance metrics

$\text{Cost to Shipper}$

$\text{Freight Flow Disrupted}$
Network Functionality Metric

Functionality at any time $t$ is defined as the ratio of some expected post-event network throughput to the pre-event network throughput (Miller-Hooks et al. 2012).

$$Q(t) = \frac{1}{\sum_{k \in K} d_k} E \left( \sum_{k \in K} d_k(t) \right)$$

where $d_k(t) = V_k \frac{1}{I_k(t)}$

$I_k(t)$ is the travel impedance function for shipment $k$ at time $t$

$d_k(t)$ is the post-event network throughput for shipment $k$ at time $t$

$d_k^-$ is the pre-event network throughput for shipment $w$ at time $t$

$V_k$ is the value of goods in shipment $k$

$k \in K$ is the set of all shipments being transported.
Functionality at any time $t$ is defined as the ratio of some expected post-event network throughput to the pre-event network throughput (Miller-Hooks et al. 2012).
Optimal Restoration Scheduling

Crew assignment
Restoration of bridge functionality

• The optimal restoration scheduling algorithm restores all the bridges necessary for fulfilling the predefined network demands in the most efficient manner permissible under given resource constraints.

Collaboration with Andres Gonzalez (OSU)
Role of transportation infrastructure in modeling community resilience under hurricane hazards

- *Galveston, TX*

E. Fereshtehnejad, I. Gidaris, N. Rosenheim, T. Tomiczek, J.E. Padgett, D.T. Cox, S. Van Zandt, W. G. Peacock (*Accepted*).

Probabilistic risk assessment of coupled natural-physical-social systems: the cascading impact of hurricane-induced damages to civil infrastructure in Galveston, Texas. *Natural Hazards Review*
Coupled Systems

- Integrated resilience framework incorporating physical and social systems

Physical systems

- Buildings
- Bridges
- Roadways

Social systems

- Population evacuation behavior
- Household-level surveys

Integrated decision-support framework

Hazard models

Transportation network connectivity evaluation

Probabilistic hybrid physical/social performance measures

Identification of resilience enhancement strategies
• Surrogate models of joint hazard potential
  ▪ Storm surge and wave modeling:
    • High computational cost
    • Prohibitive for probabilistic analysis
  ▪ Kriging modeling using a suite of 228 storms (USACE, 2015):

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge height ($S(\omega)$)</td>
<td>2.4</td>
</tr>
<tr>
<td>Significant wave height ($H_s(\omega)$)</td>
<td>7.6</td>
</tr>
<tr>
<td>Peak wave period ($T_p(\omega)$)</td>
<td>6.8</td>
</tr>
</tbody>
</table>

See for example Jia and Taflanidis (2013) or Bernier and Padgett (2019)
Input models developed for key network components

Bridges

Ataei and Padgett (2012)

Fragility Models

Restoration Models

Roads

Gidaris et al. (2019)
Temporal Evolution of Recovery

• Recovery is prioritized based on the importance of the component in the overall connectivity of the transportation network.

• The number of available crews for roadway and bridge recovery is variable.
Connectivity to Emergency Services

- Probability of disconnection of households from emergency services

Inland | Fire Stations | Medical Centers

![Maps showing connectivity to emergency services](image)

Legend:
- PNC: Probability of Not Connected
- Annual Probability
- Color codes for probability ranges
Hybrid Social-Physical Metrics

- Integrated physical/social performance metrics

Probability of households being hot: 1) Damaged 2) Non-evacuees inside, and 3) Disconnected from emergency/medical services
Conclusions, Challenges and Opportunities

Address Fragility and Restoration Knowledge Gaps

- Fragility functions
- Restoration models

Enhance Systems Analysis and Coupling

- Physics-based and first principle models
- IM (intensity measure)
Conclusions, Challenges and Opportunities

Pursue “Smart Resilience”

- Leverage diverse and emerging data sources
  - Resilience and sustainability assessment
  - Situational awareness

Figure 1. Data sources informing Smart Situational Awareness of Flood impacts on Transportation infrastructure (SSAFT).
Conclusions, Challenges and Opportunities

Promote a Culture of Data Sharing

- Embrace coordinated data collection, curation and publication across urban scales and systems
- Leverage cyberinfrastructure platforms like DesignSafe
- Enable future data fusion, AI/ML/DL informing resilience quantification
- Support opensource code and software development


https://incore.ncsa.illinois.edu/
Thank you

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