Resilience of Intermodal Transportation Infrastructure under Multiple Hazards

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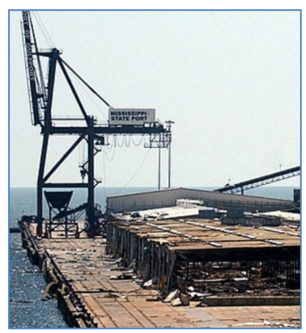
Research Focus and Topics of Interest

Structural reliability and natural hazard risk mitigation

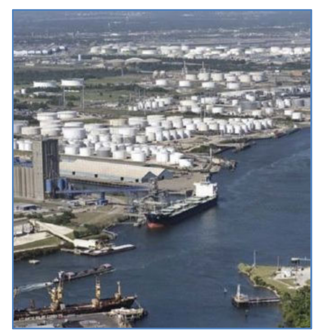
- Key emphases in the areas of
  - Portfolio structural vulnerability analysis and protection
  - Multi-hazard assessment (earthquake, surge, wave, aging…)
  - Sustainability and resilience quantification
- Application to transportation and energy/industrial infrastructure

Bridges

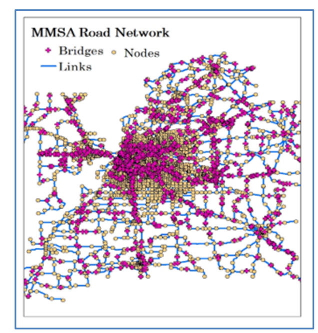
Above Ground Storage Tanks



Port Structures and Facilities



Industrial Complexes and Communities



Regional Scale Transportation

Our Group at Rice University

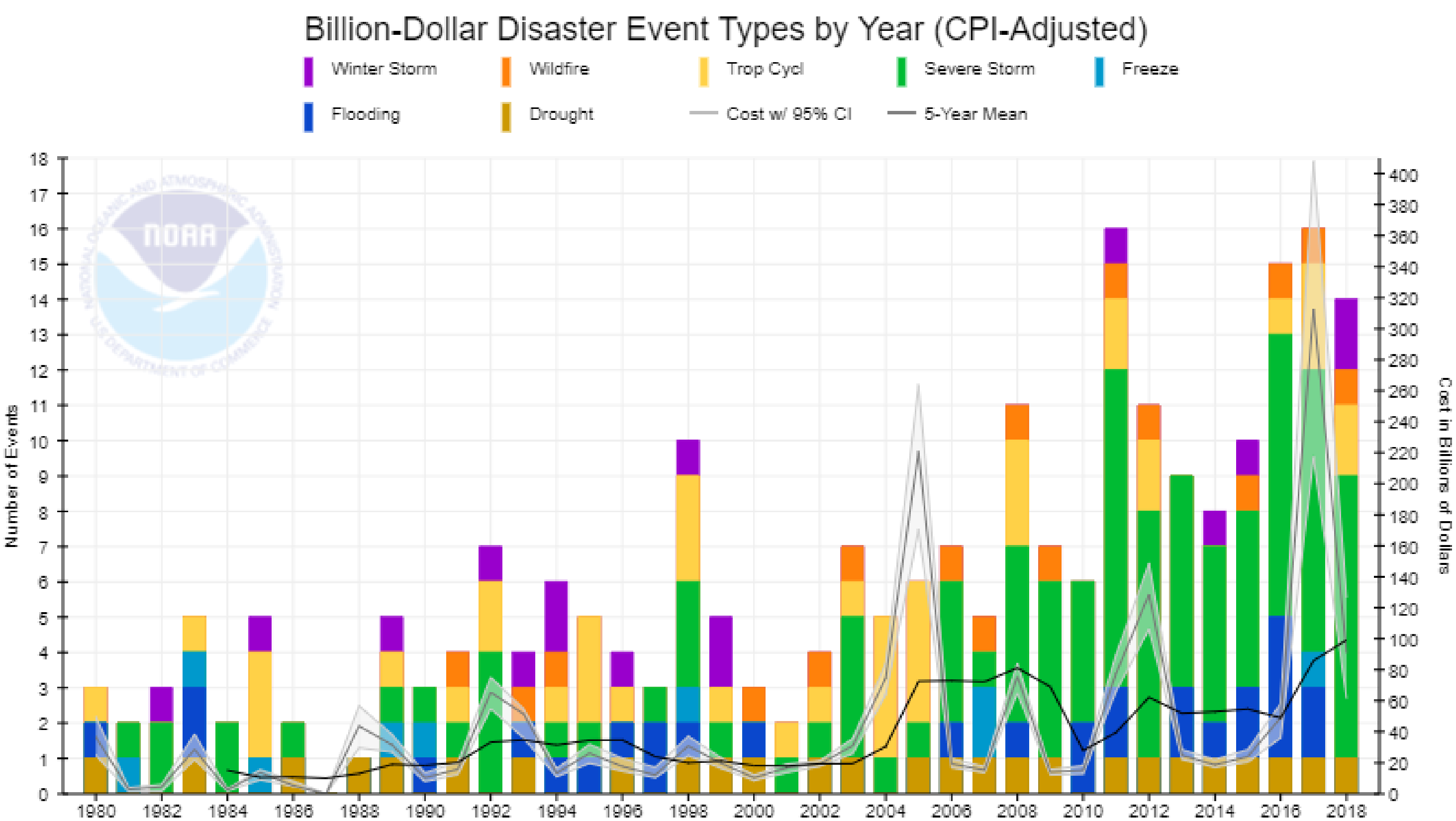
RICE

A Multi-Hazard World

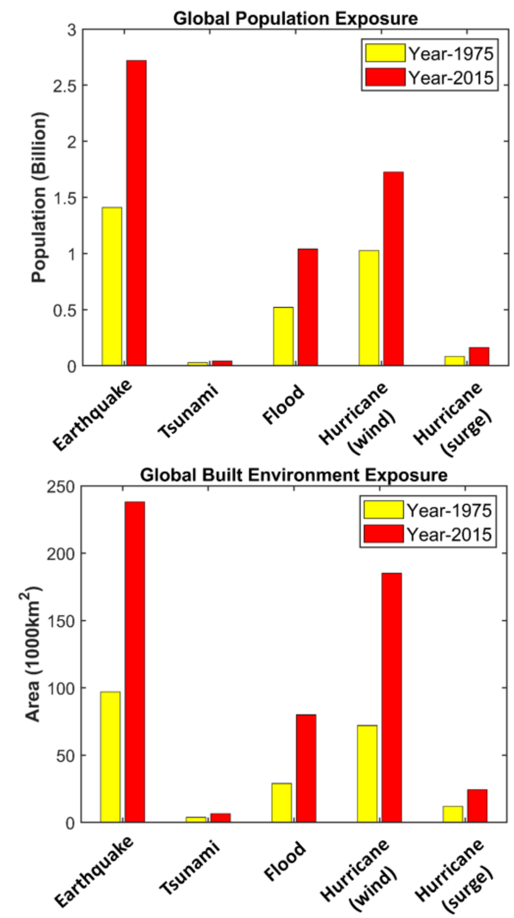
Figure 1. Dominant hazard per region based on infrastructure exposure (Koks et al. 2019)

Koks et al. (2019) "A global multihazard risk analysis of road and railway infrastructure assets" *Nature Communications*. https://doi.org/10.1038/s41467-019-10442-3

Increasing Hazard Exposures and Losses



(Source: NOAA 2019)

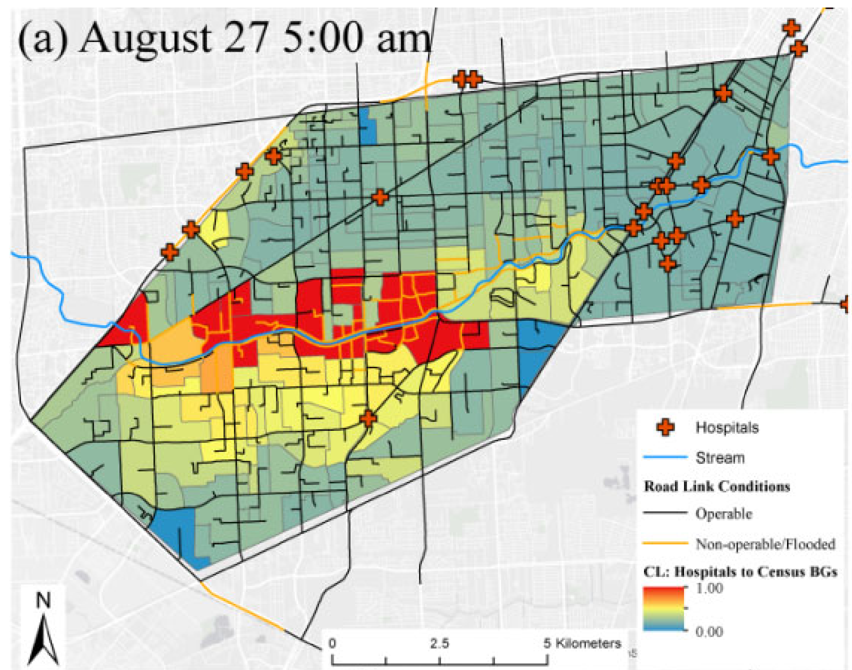


(Adapted from Pesaresi et al. 2017)

Transportation Infrastructure Resilience

- Transportation infrastructure resilience is crucial during/after hazard events.

Hurricane Harvey (2017)



Gori et al. (2019)

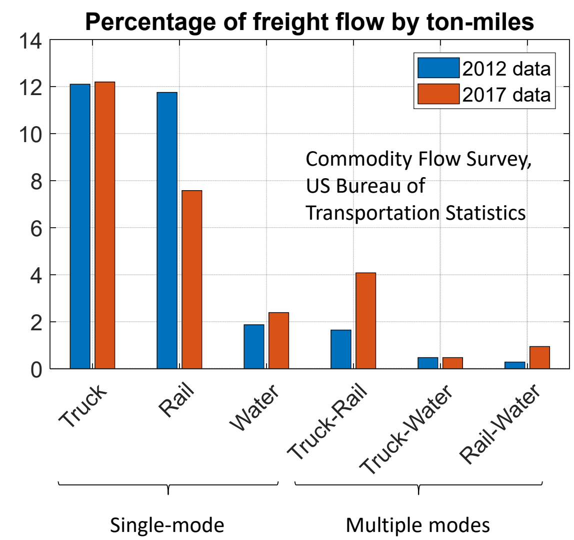
Importance of Intermodal Transport

Distorted railway track in Christchurch (2011)

Gulf Port Wharves after Hurricane Katrina (2005)

Collapsed bridge span in Kobe (1995)

- Impact of multiple hazards on transportation infrastructure
- Importance and complexity of modeling intermodal transportation systems
- Potential to disrupt goods flow



Outline

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)

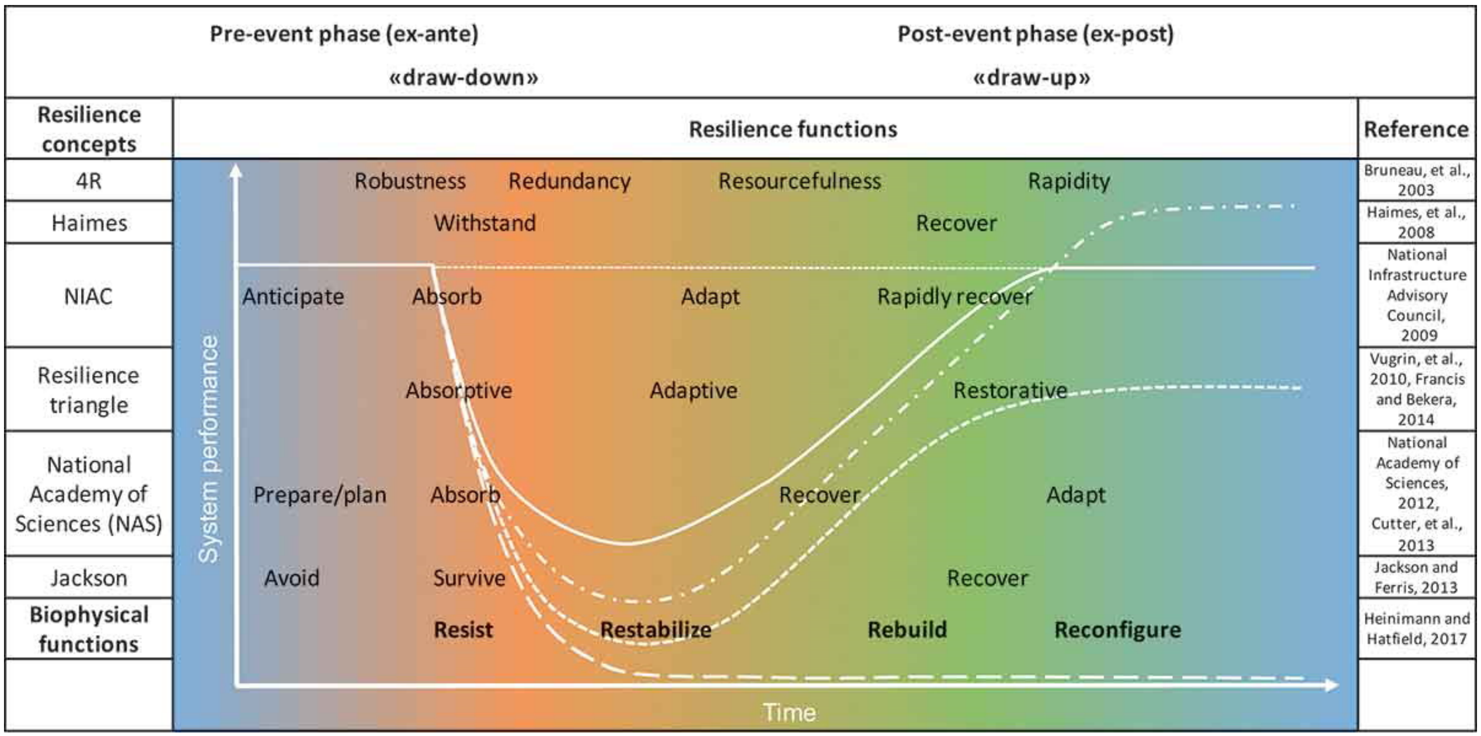
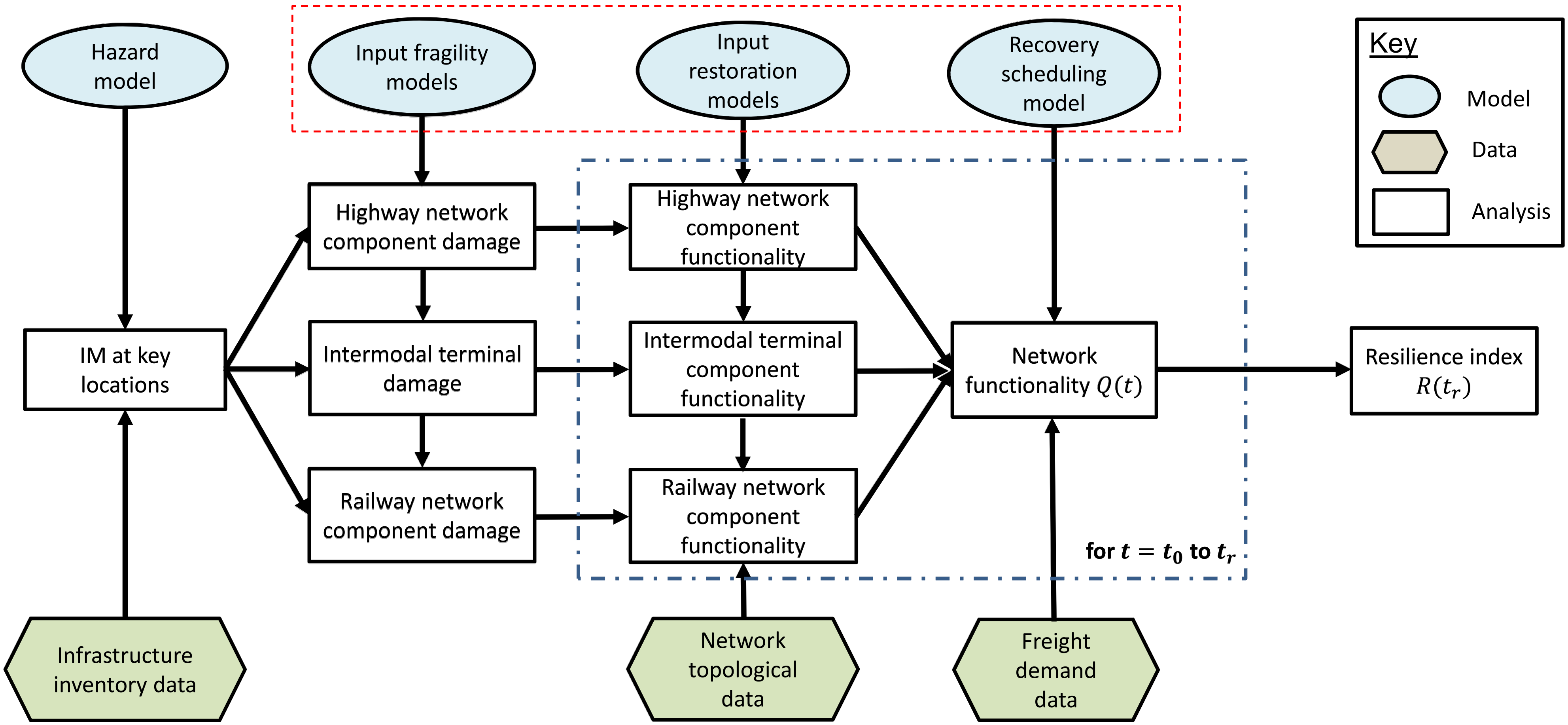


Figure 1. Example resilience characterization drawing from state-of-art review (Gasser et al. 2019)

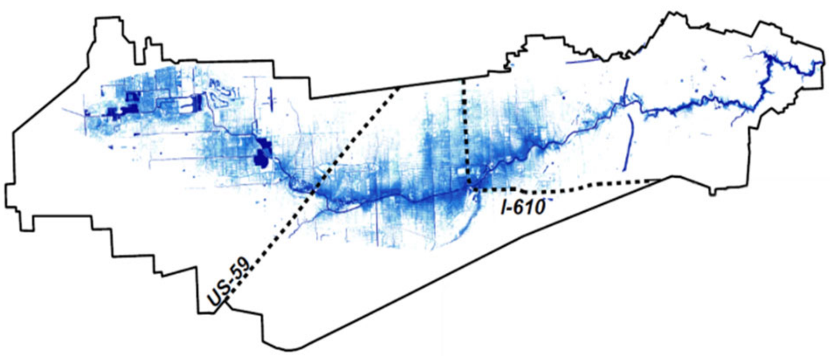
Gasser et al. (2019) “A review on resilience assessment of energy systems” *Sustainable and Resilient Infrastructure.* doi.org/10.1080/23789689.2019.1610600

Intermodal Resilience Analysis Framework

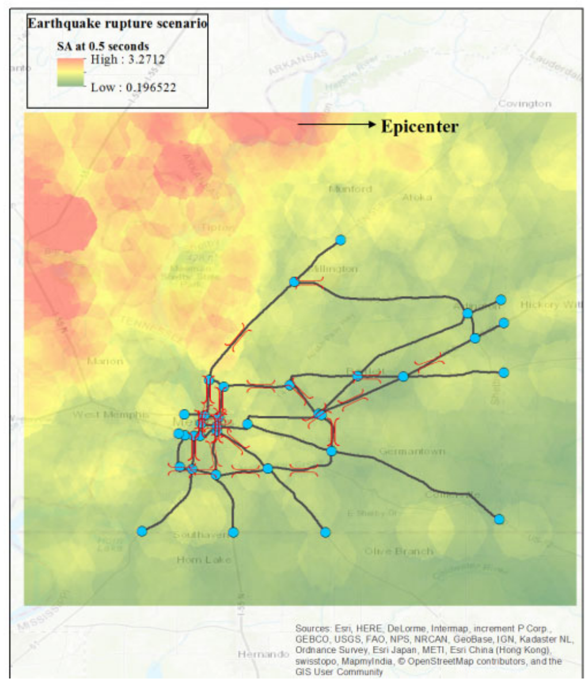


Key input: *Hazard models*

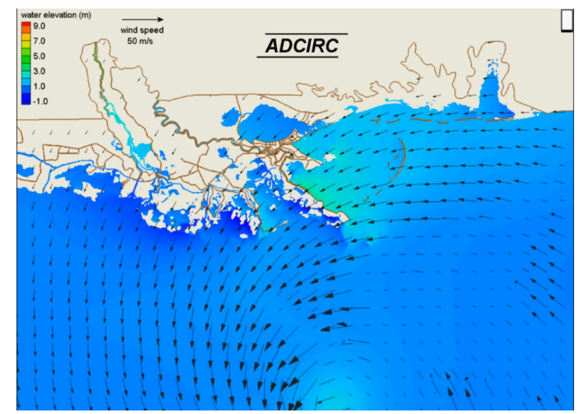
- Hazard occurrence characterization and spatial hazard intensity modeling
  - Physics based
  - Surrogate model
  - Single / multi-hazard



Flood (Gori et al. *2019*)



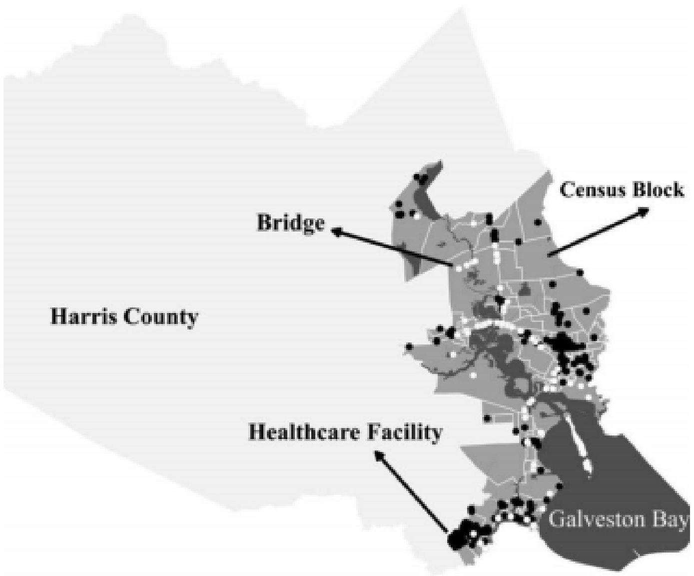
Earthquake (Vishnu et al. 2018)



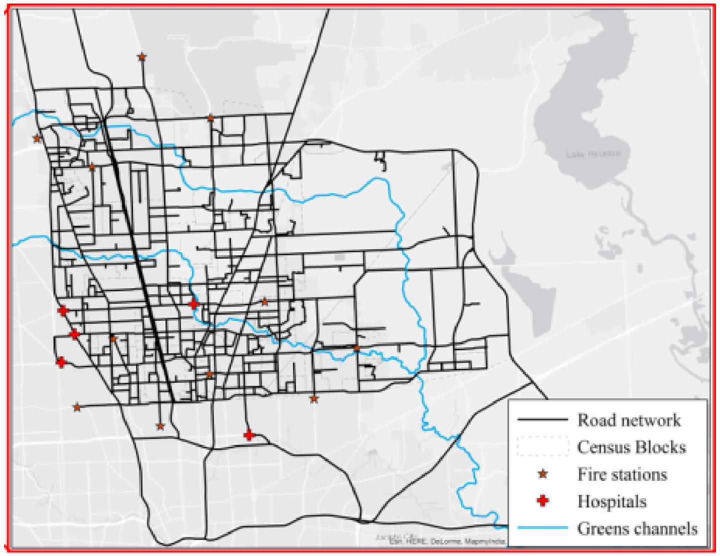
Hurricane
(Dawson et al, 2017)

Key input: *Exposure models*

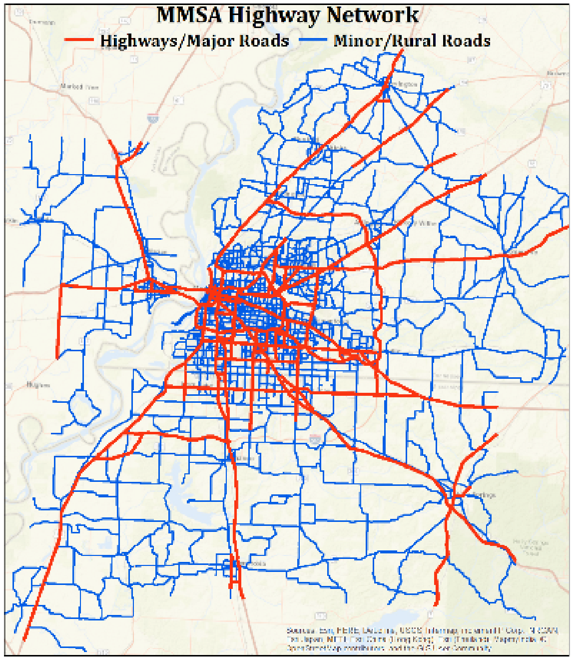
- Provide information (e.g., location, structural type, and replacement cost) of the spatially distributed structures



Balomenos et al. (2019)



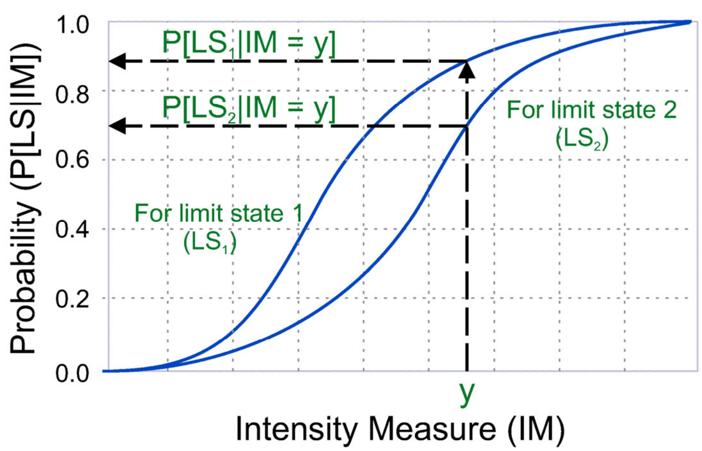
Gori et al. (2019)



Vishnu (2018)

Key input: *Fragility models*

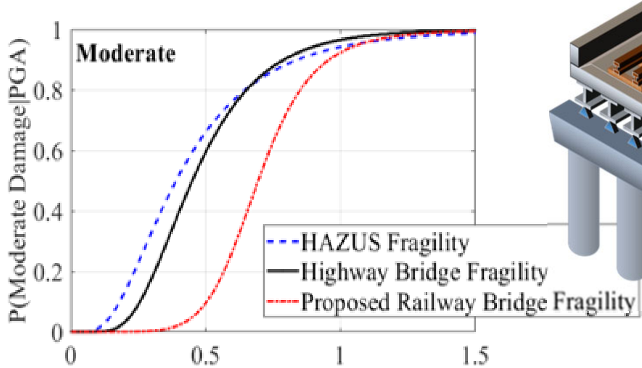
- Provide probability of exceeding a certain limit state for the structures given the hazard intensities
  - Surrogate demand modeling
  - Limit state capacity characterization
  - Fragility curves/Parameterized fragility function

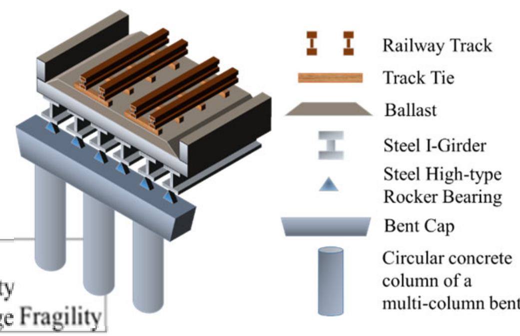


$$P(\text{Failure}|\mathbf{IM}, \mathbf{X}) = \frac{1}{1 + \exp(-l(\mathbf{IM}, \mathbf{X}))}$$

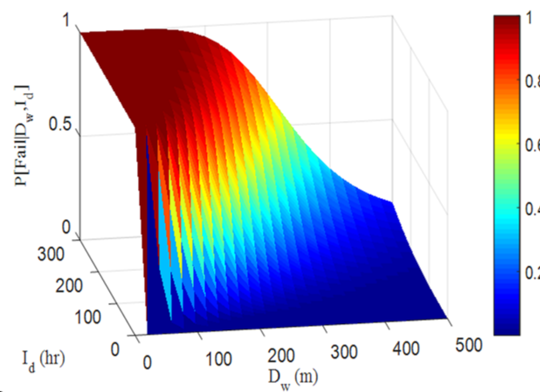
Logit function

Key input: *Fragility models*

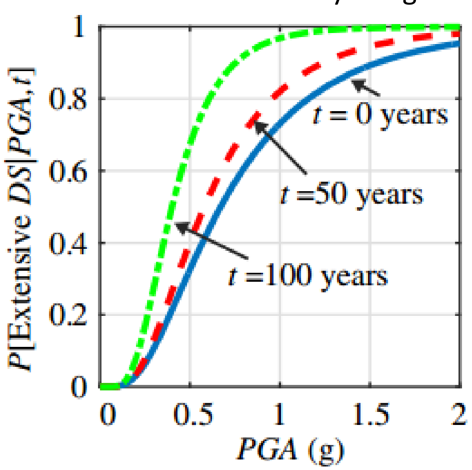




Railway bridge fragility (Misra & Padgett, 2019)

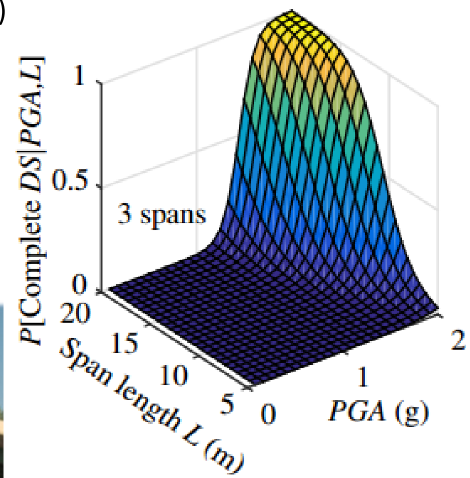


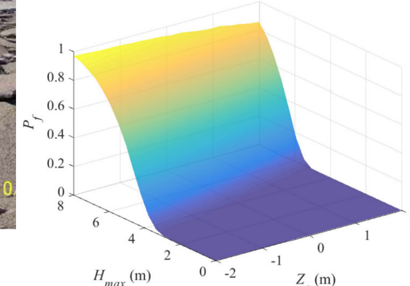
Roadway fragility (Gidaris et al., 2019)



Time-dependent bridge fragility (Ghosh & Padgett, 2010)

Parameterized highway bridge fragility (Kameshwar & Padgett, 2014)



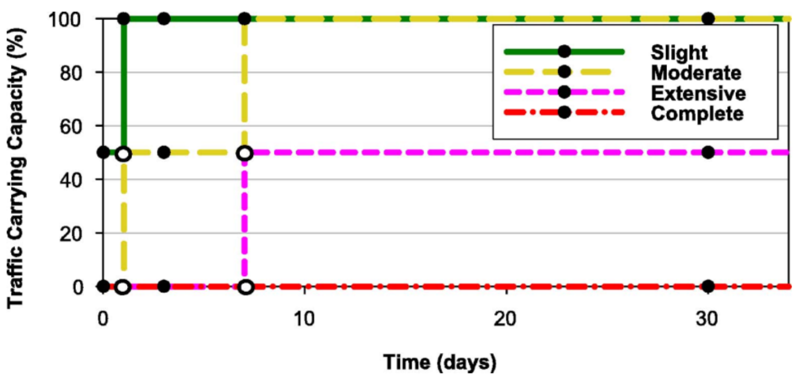


Piers and wharfs at ports (Balomenos and Padgett, 2019)

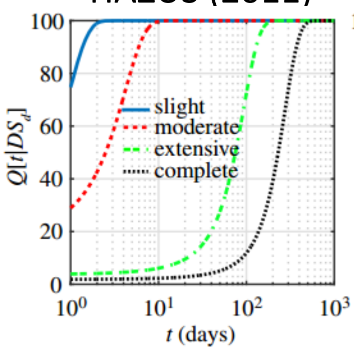
Key input: *Restoration models*

- Quantify temporal functionality and restoration of structures & systems

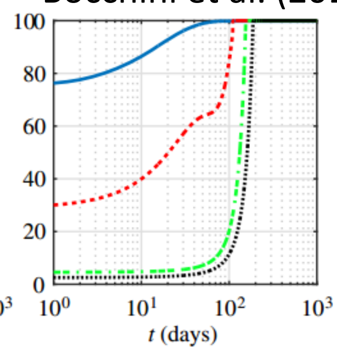
Padgett & DesRoches. (2007)



HAZUS (2011)

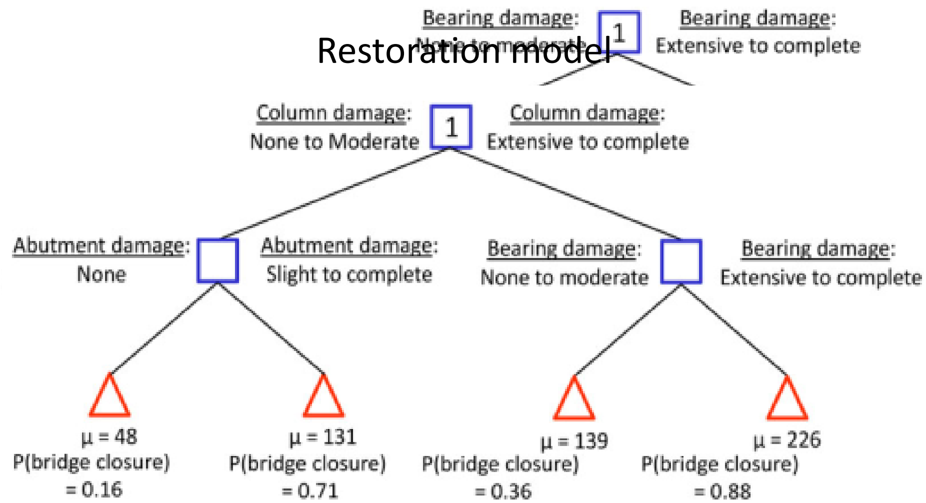


Bocchini et al. (2012)



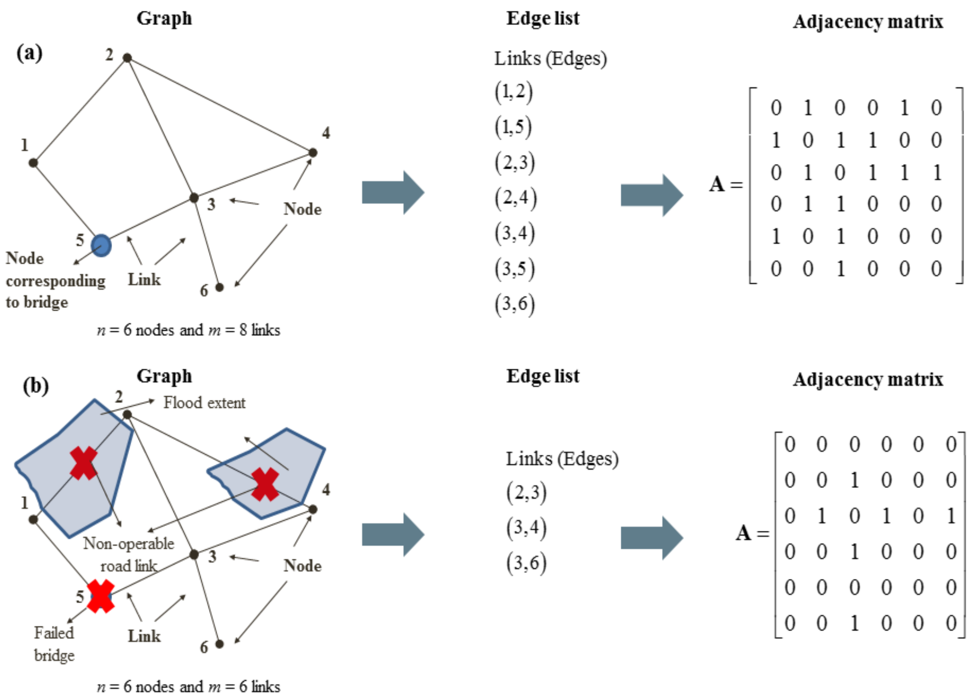
Functionality model

Restoration model

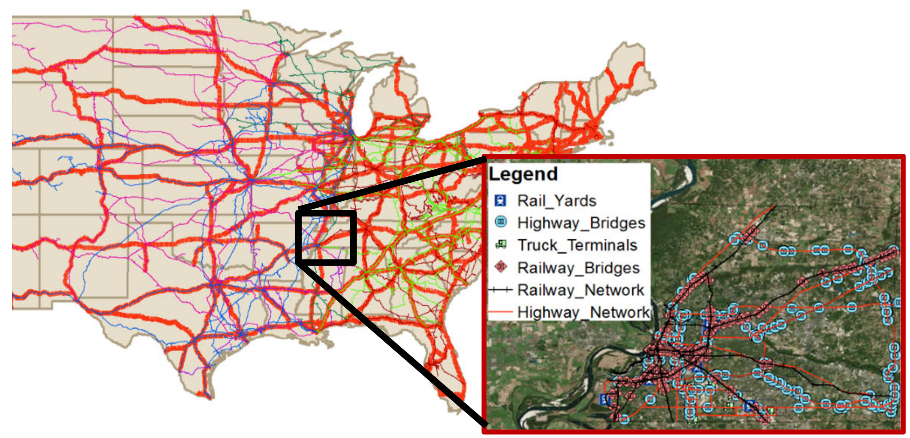


Kameshwar et al. (2019)

Key input: *Recovery Scheduling and Network Analysis*



Bernier et al. (2019)



Misra and Padgett (2019)

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

Example #1

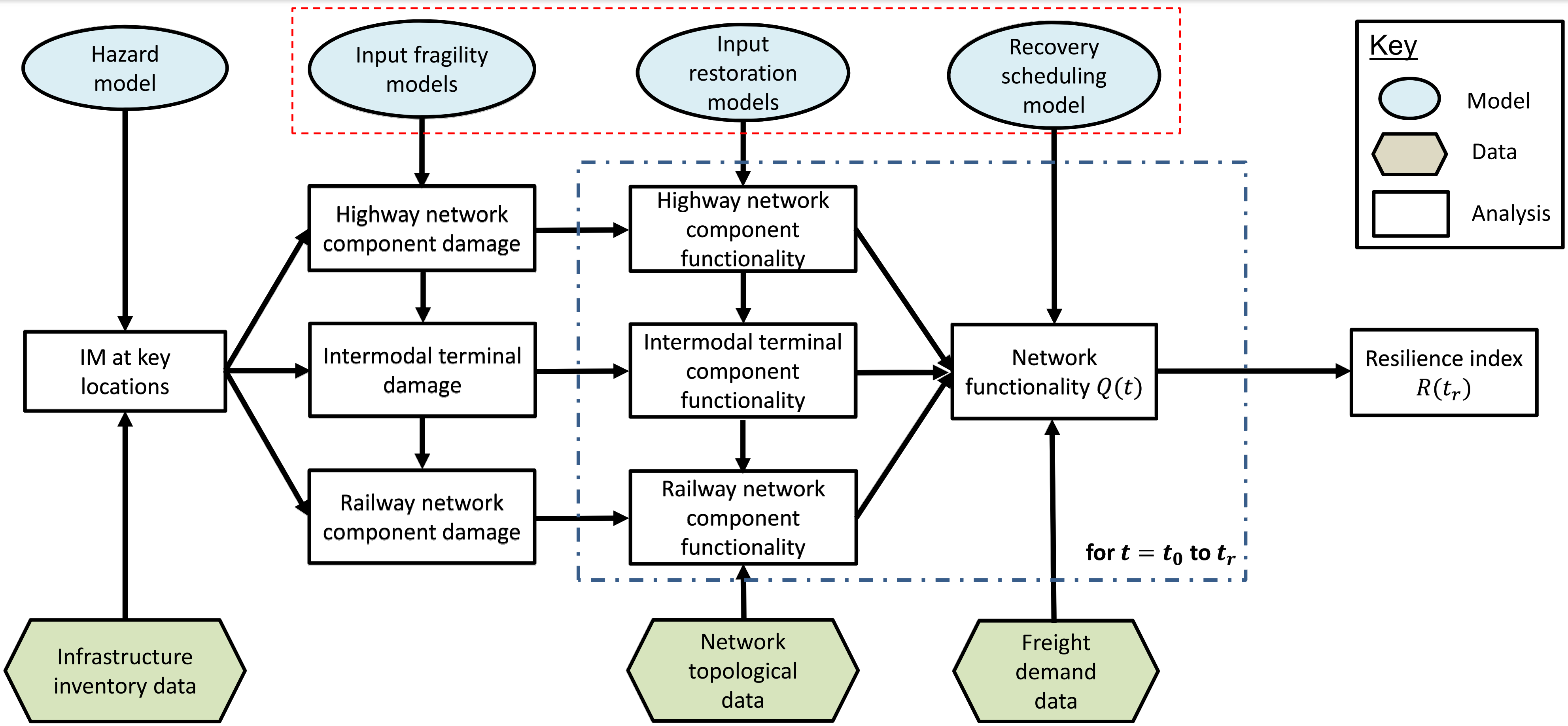
Seismic Resilience Modeling of Rail-Truck Intermodal Transportation Networks

- *Memphis Metropolitan Statistical Area (MMSA)*

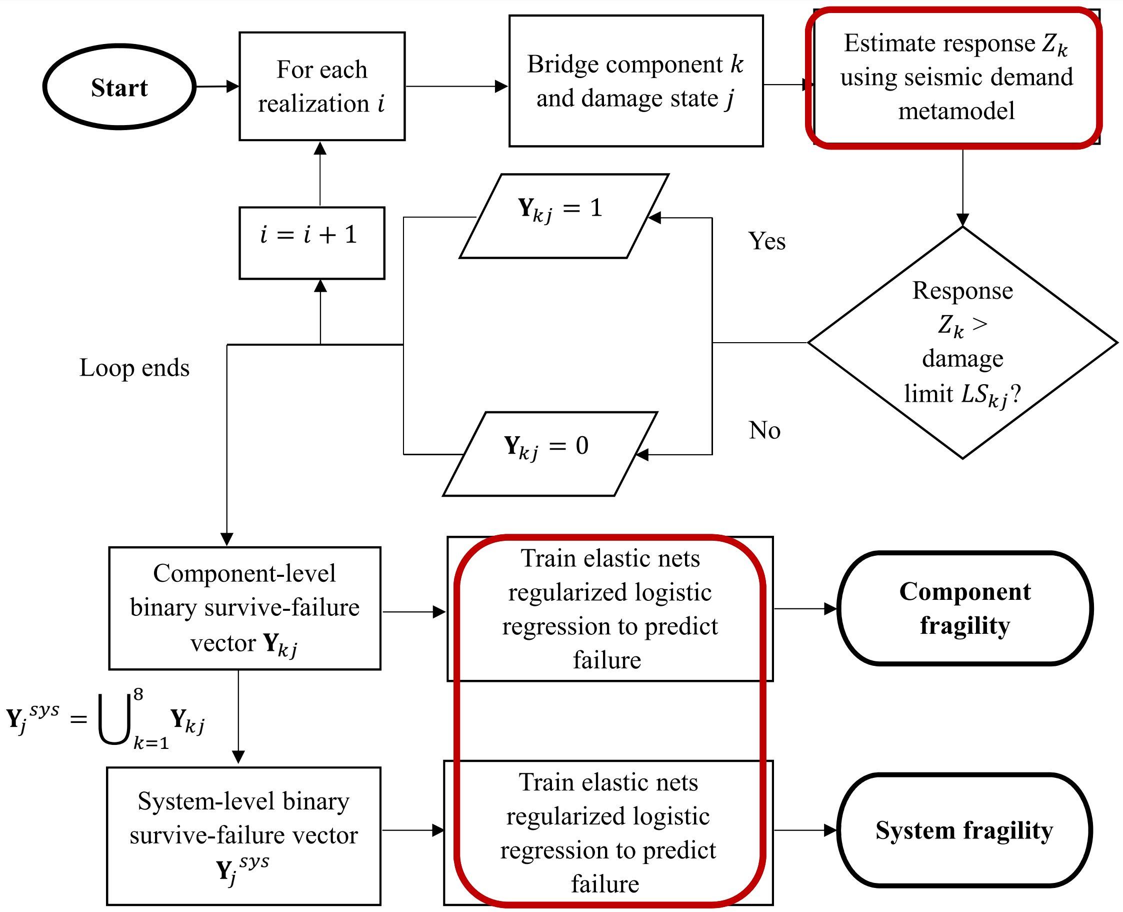
+

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*

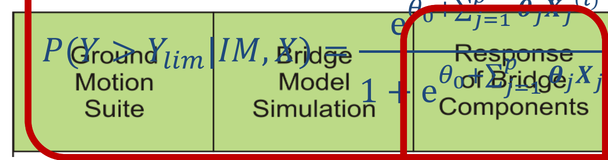
Intermodal Resilience Analysis Framework

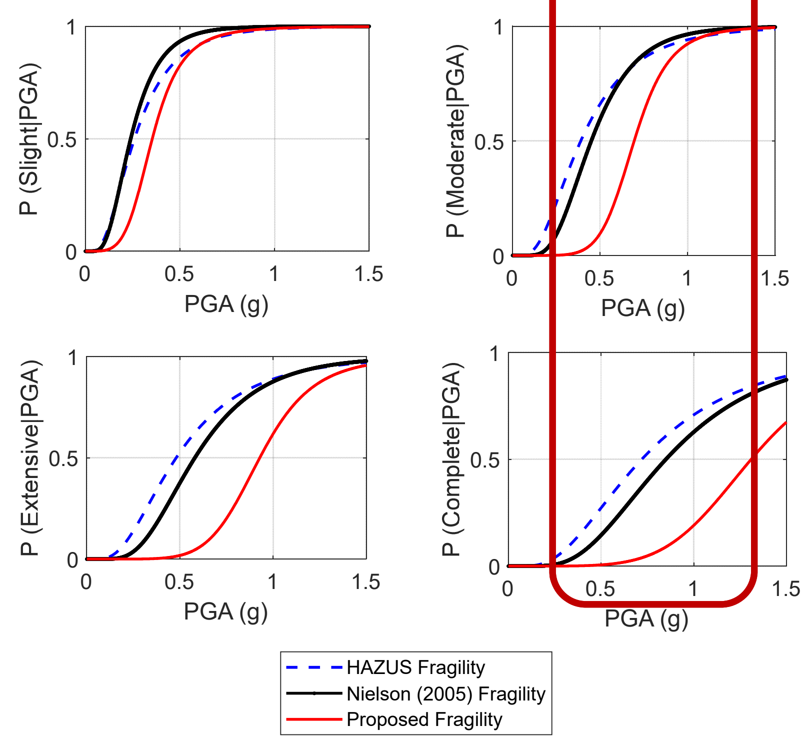


Parameterized Fragility Method



$$P(Y > Y_{lim} | IM, X) = \frac{e^{\theta_0 + \sum_{j=1}^{p} \theta_j X_j^{(i)}}}{1 + e^{\theta_0 + \sum_{j=1}^{p} \theta_j X_j^{(i)}}}$$



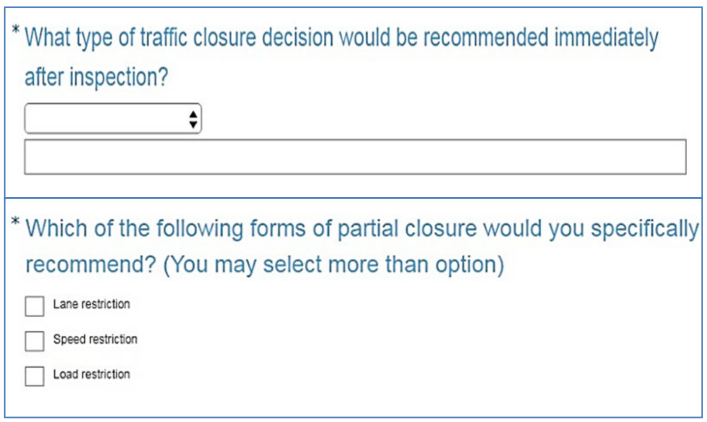


Misra, S., & Padgett, J. E. (2019). Seismic Fragility of Railway Bridge Classes: Methods, Models, and Comparison with the State of the Art. *Journal of Bridge Engineering*, *24*(12), 04019116.

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.

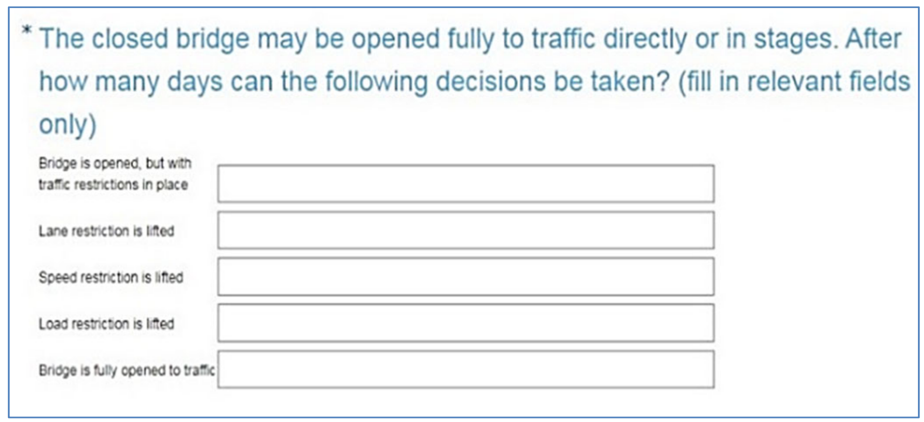
- Goals of the surveys – harvest data relating various damage levels (component damage for bridges) to ***closure decisions*** (both complete and partial) and their ***durations***.



* What type of traffic closure decision would be recommended immediately after inspection?

* Which of the following forms of partial closure would you specifically recommend? (You may select more than option)

- Lane restriction
- Speed restriction
- Load restriction



* The closed bridge may be opened fully to traffic directly or in stages. After how many days can the following decisions be taken? (fill in relevant fields only)

Bridge is opened, but with traffic restrictions in place

Lane restriction is lifted

Speed restriction is lifted

Load restriction is lifted

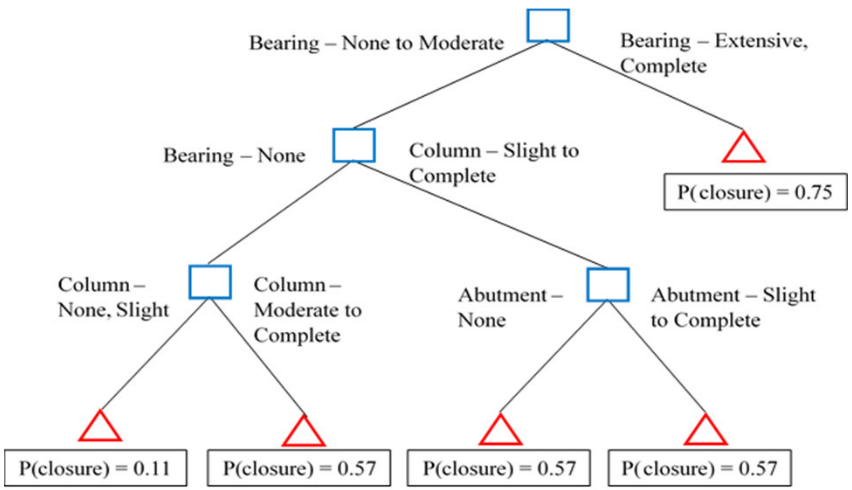
Bridge is fully opened to traffic

[1] Misra, S., Padgett, J. E., Barbosa, A. R., & Webb, B. M. (2020). An expert opinion survey on post-hazard restoration of roadways and bridges: Data and key insights. *Earthquake Spectra*, *36*(2), 983-1004.

[2]Misra, S. and J. E. Padgett. (2017). Post-Earthquake Restoration Modelling of a Railway Bridge Network. *ASCE Congress on Technical Advancement*, Duluth, Minnesota, 10-13 September 2017.

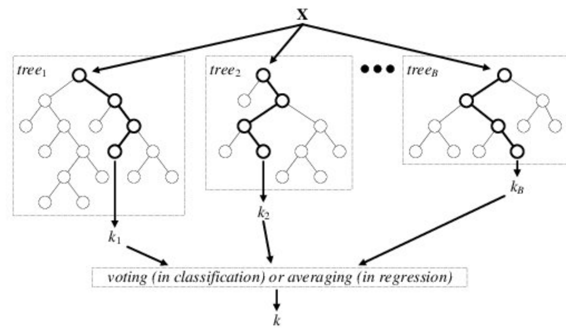
Highway / Railway Bridge Restoration Modeling

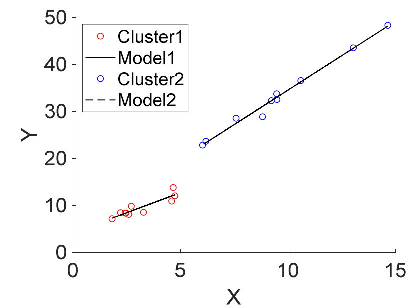
Models for closure decision



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

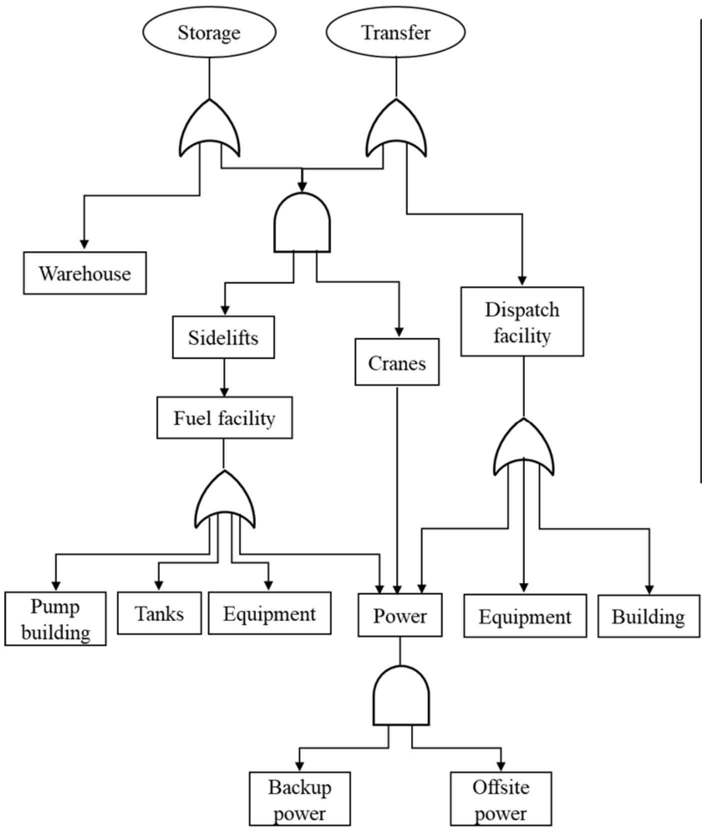
Models for closure duration

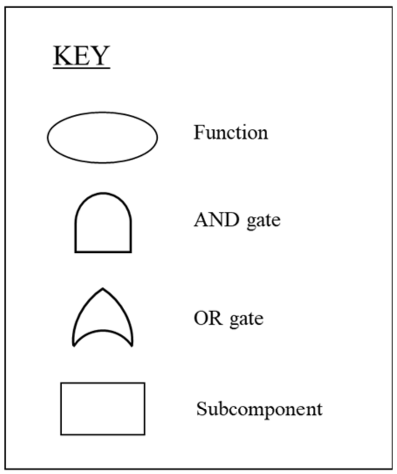




- **Clustered random forests** are leveraged
- Random forests – ensemble of decision trees
- Data divided into clusters – separate model fit to each cluster
- Reduces variance of predicted durations

Restoration Models for Intermodal Terminals

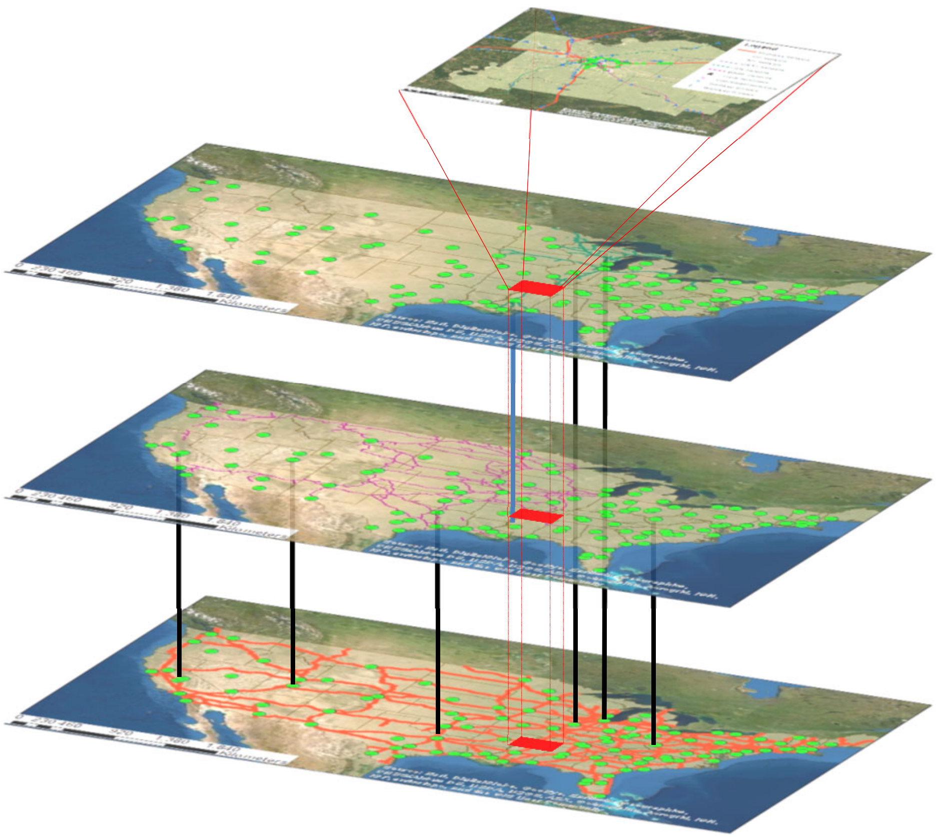




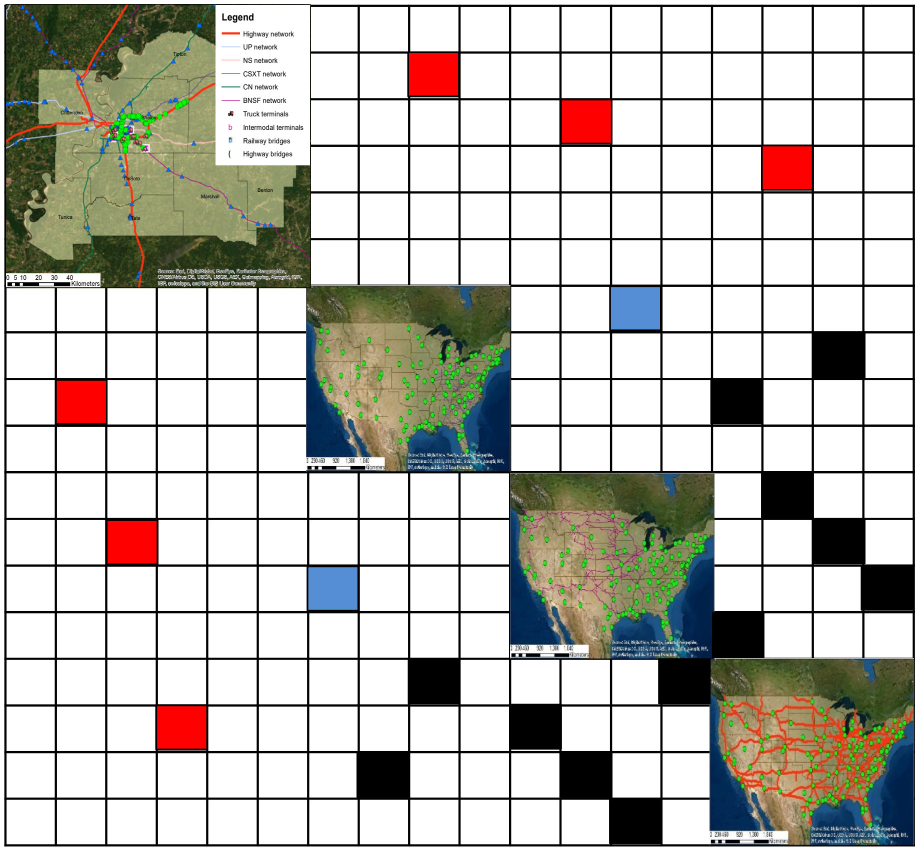
- A schematic ***fault tree model*** is proposed to illustrate the functional dependencies between the components and subcomponents of the intermodal terminal
- An AND connector indicates that all the subcomponents listed under the gate (children) must fail for the parent node to fail
- OR connector 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



Optimization Problem

Minimize $\alpha \times O1 + (1 - \alpha) \times (O2 + O3 + O4)$

- $O1$ = Cost of repair — Owner's cost
- $O2$ = Cost of freight transport
- $O3$ = Cost of unmet demands
- $O4$ = Cost of excess supply

($O2$–$O4$: Shipper's cost)

Subject to

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

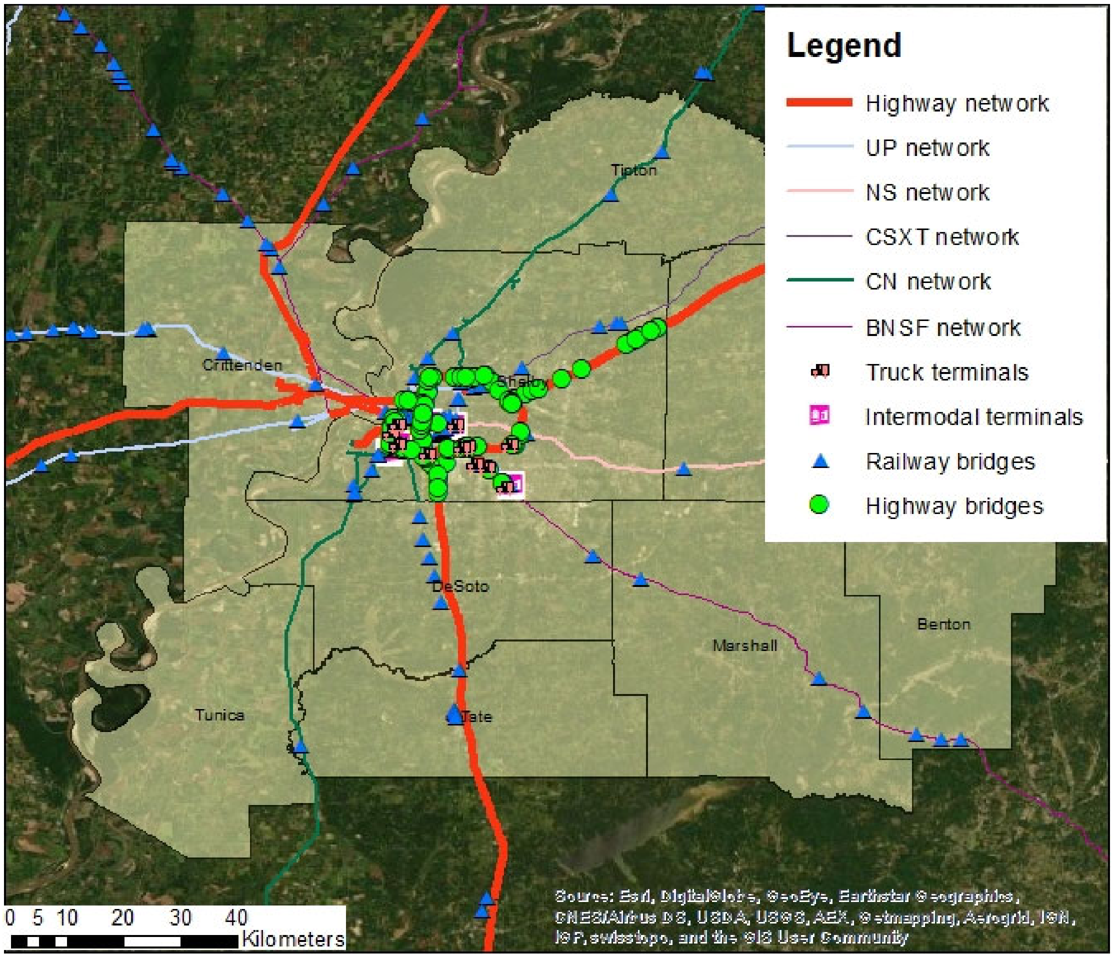
Key Decision Variables	Description
Δy_{bt}	Binary variable stating if crews are assigned to component b at time t
y_{bt}	Functionality of component b at time t
x_{ijtk}	Freight containers on link ij at time t carrying shipment k

Gomez, C., González, A. D., Baroud, H., & Bedoya-Motta, C. D. (2019). *Risk Analysis*, *39*(9), 1913-1929.

González, A. D., Chapman, A., Dueñas-Osorio, L., Mesbahi, M., & D'Souza, R. M. (2017). *Computer-Aided Civil and Infrastructure Engineering*, *32*(12), 991–1006.

Collaboration with Andres Gonzalez (OSU)

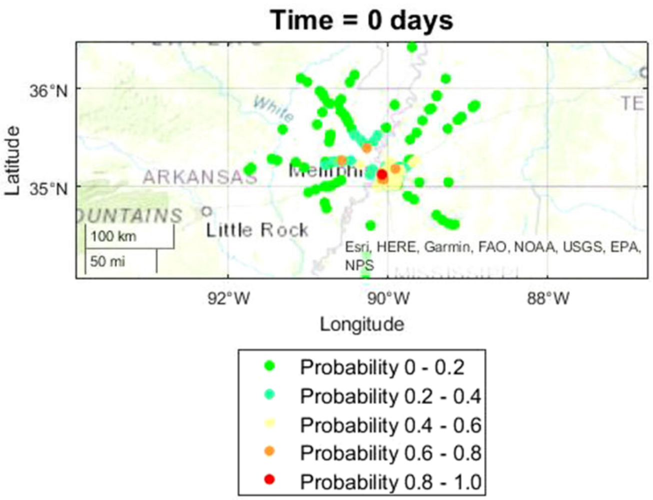
Testbed Regional Intermodal Network



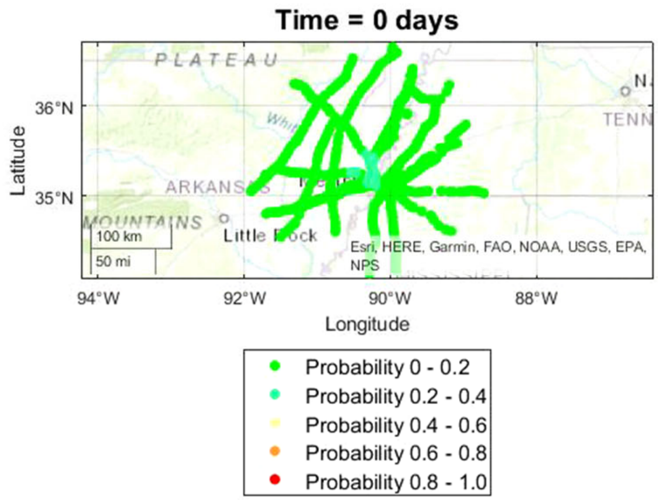
- Testbed regional intermodal network: Memphis, TN
- 5 Class I railroads operate in the region (BNSF, CN, CSXT, NS and UP)
- Hub of freight traffic
  - 153 highway bridges
  - 202 railway bridges
  - 6 intermodal terminals
- Scenario earthquake
  - Magnitude ***7.7***
  - Point source at $[\mathbf{35.3^\circ N}, \mathbf{90.3^\circ W}]$

Evaluation of Network Component Functionality

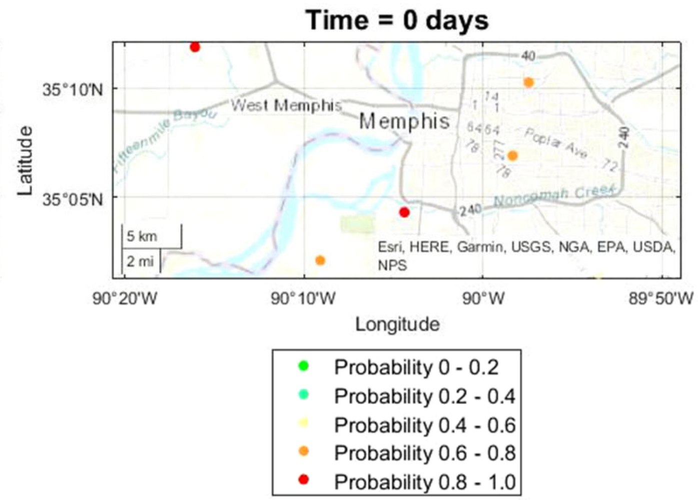
<u>Bridges – probability of closure</u>



<u>Roadways and railway tracks – probability of closure</u>



<u>Intermodal terminals – probability of failure</u>



- 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

Time Evolving Network Performance

- Network performance over time

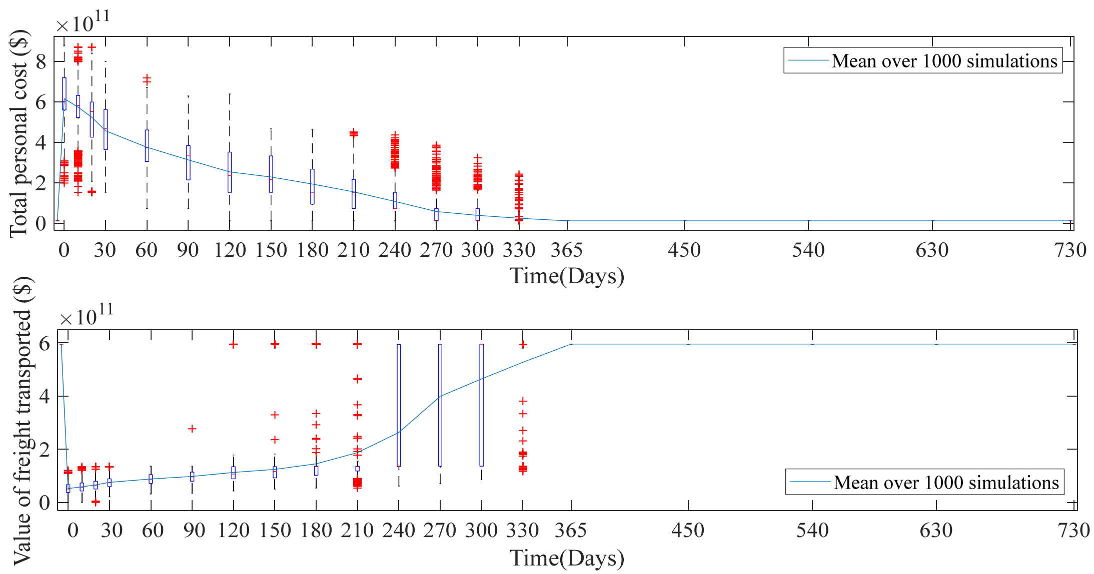


Figure 1. Example intermodal performance metrics

$ Cost to Shipper

$ 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

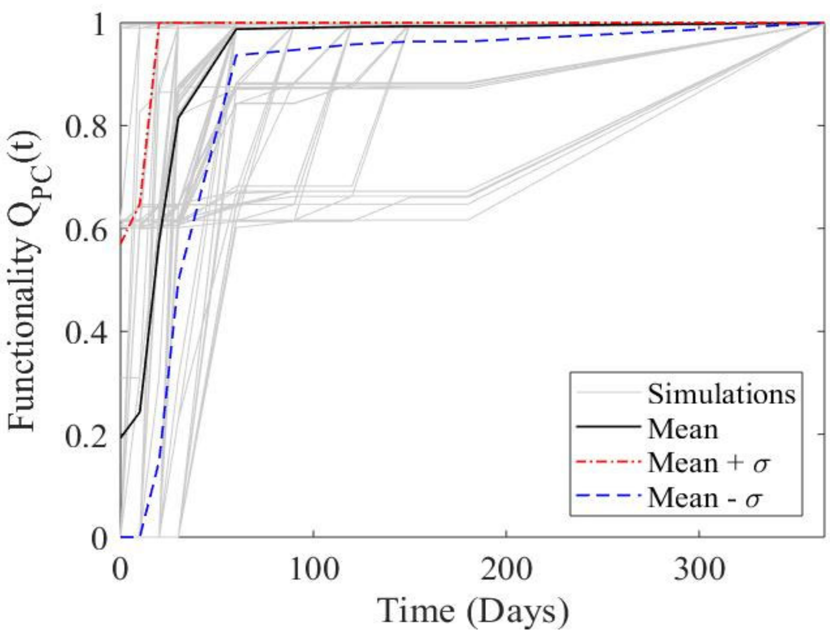
d_k^{-} is the **pre-event network throughput** for shipment w at time t

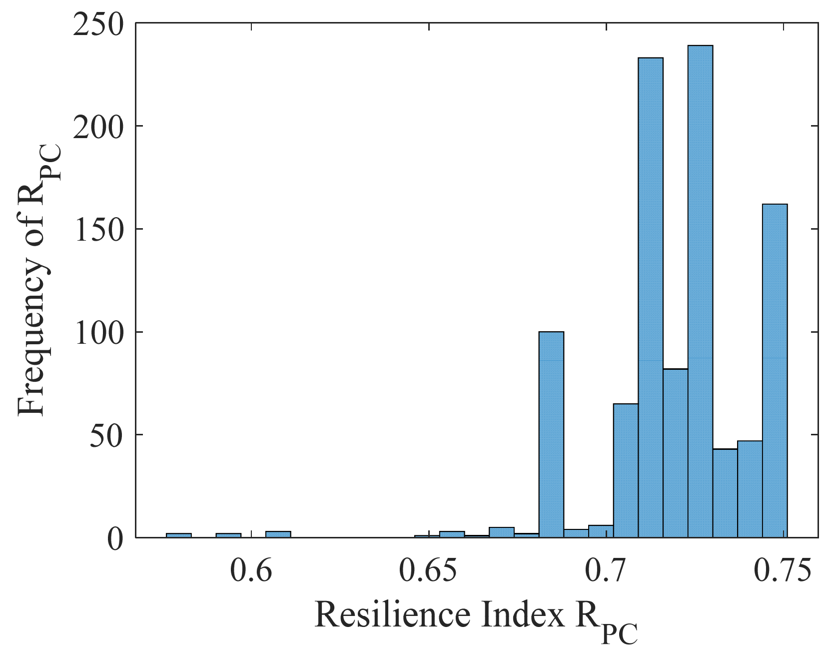
V_k is the value of goods in shipment k

$k \in K$ is the set of all shipments being transported.

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).





Optimal Restoration Scheduling

Crew assignment

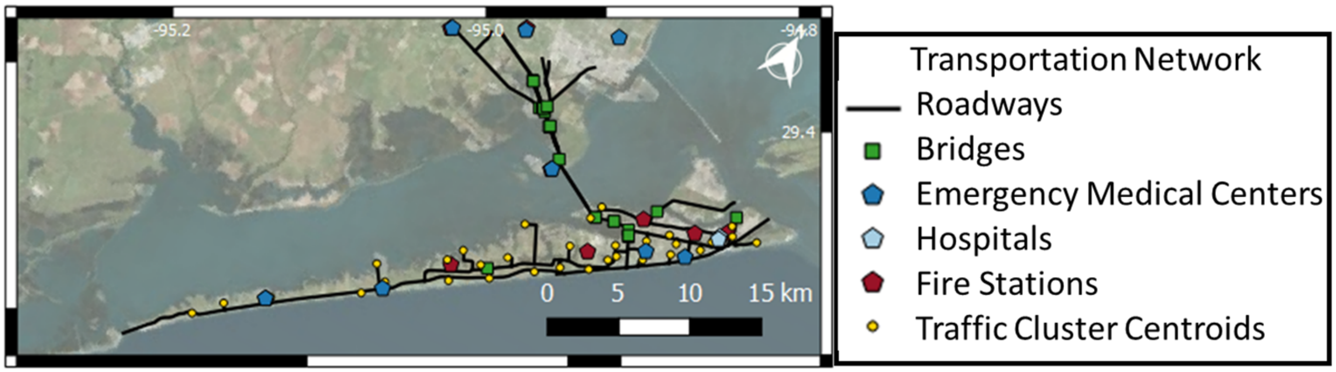
Restoration of bridge functionality

- 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)

Example #2

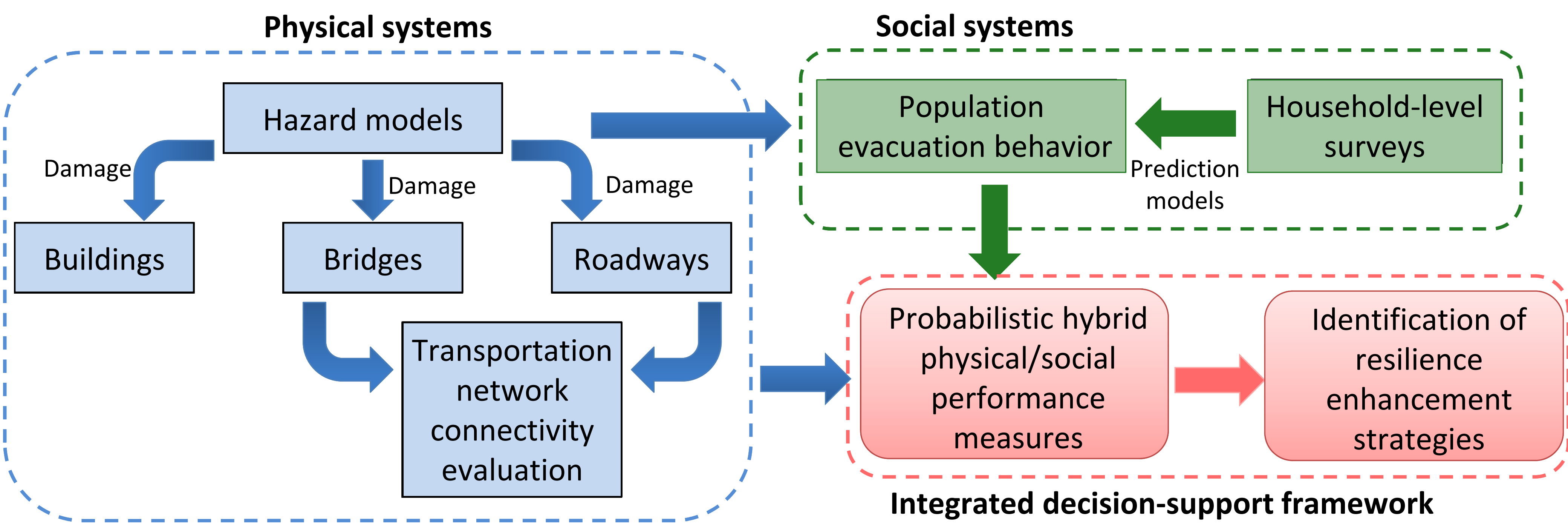
Role of transportation infrastructure in modeling community resilience under hurricane hazards
- *Galveston, TX*



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**

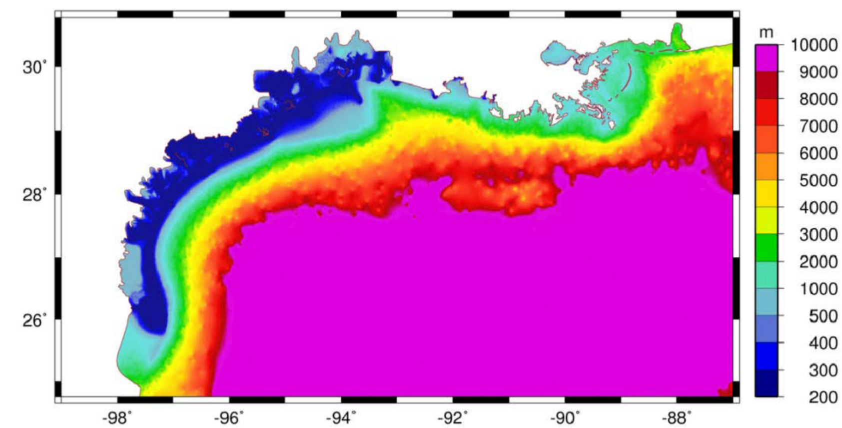


Multi-Hazard Modeling

- 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):

Model	Mean error (%)
Surge height ($S(\boldsymbol{\omega})$)	2.4
Significant wave height ($H_s(\boldsymbol{\omega})$)	7.6
Peak wave period ($T_p(\boldsymbol{\omega})$)	6.8

Texas coast ADCIRC mesh cell size (USACE, 2015)



$$\boldsymbol{\omega} = [x_o \; \varphi \; \Delta_p \; R_m \; V_f]$$

Landfall location; Storm heading (direction); Pressure deficit (intensity); Radius of max winds (size); Forward speed

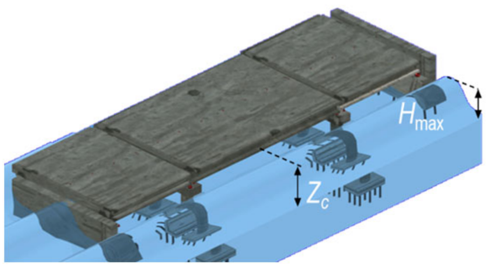
See for example Jia and Taflanidis (2013) or Bernier and Padgett (2019)

Fragility and Restoration Modeling

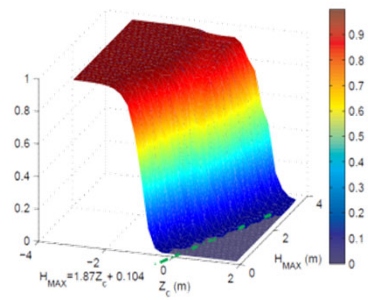
- Input models developed for key network components

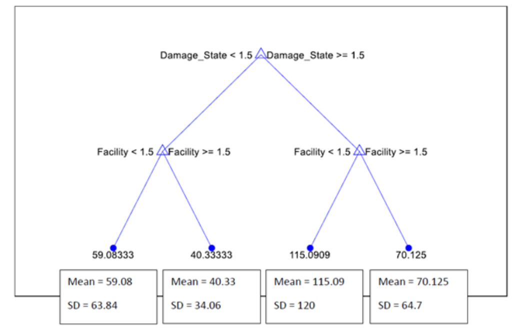
		Fragility Models	Restoration Models

Bridges

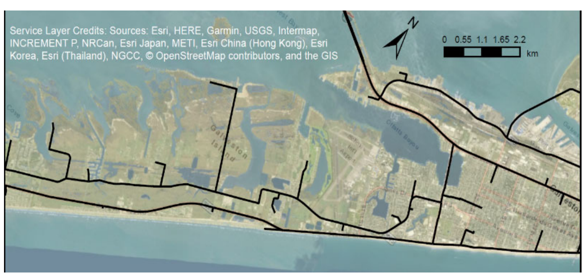


Ataei and Padgett (2012)

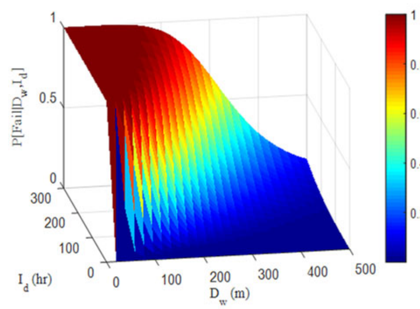


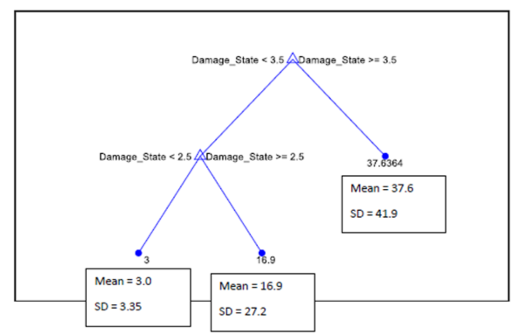


Roads



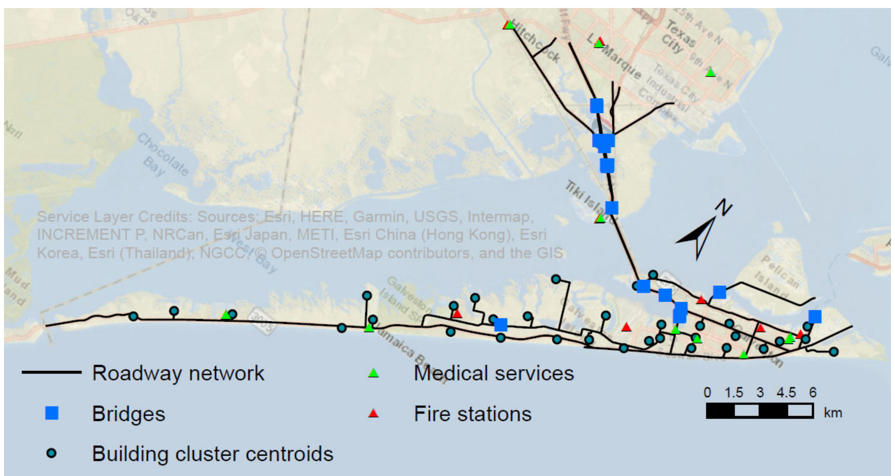
Gidaris et al. (2019)

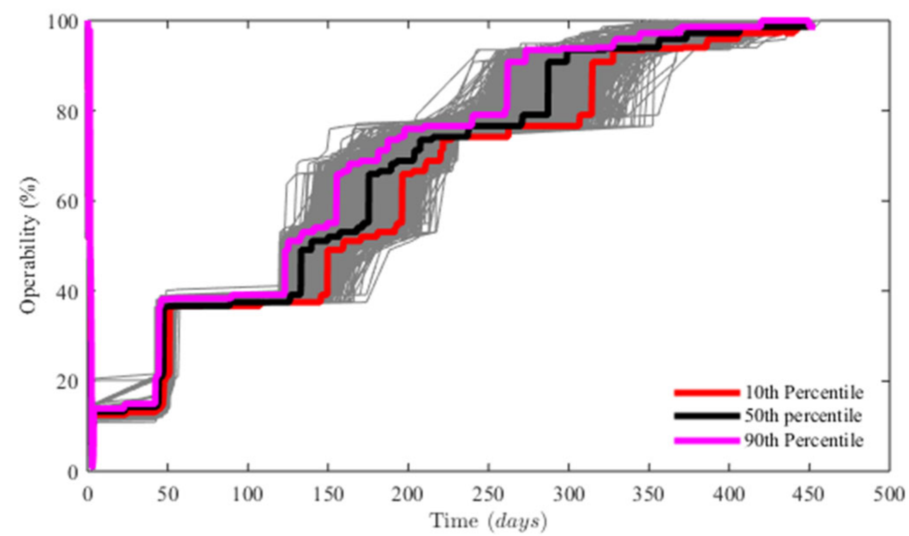




Temporal Evolution of Recovery

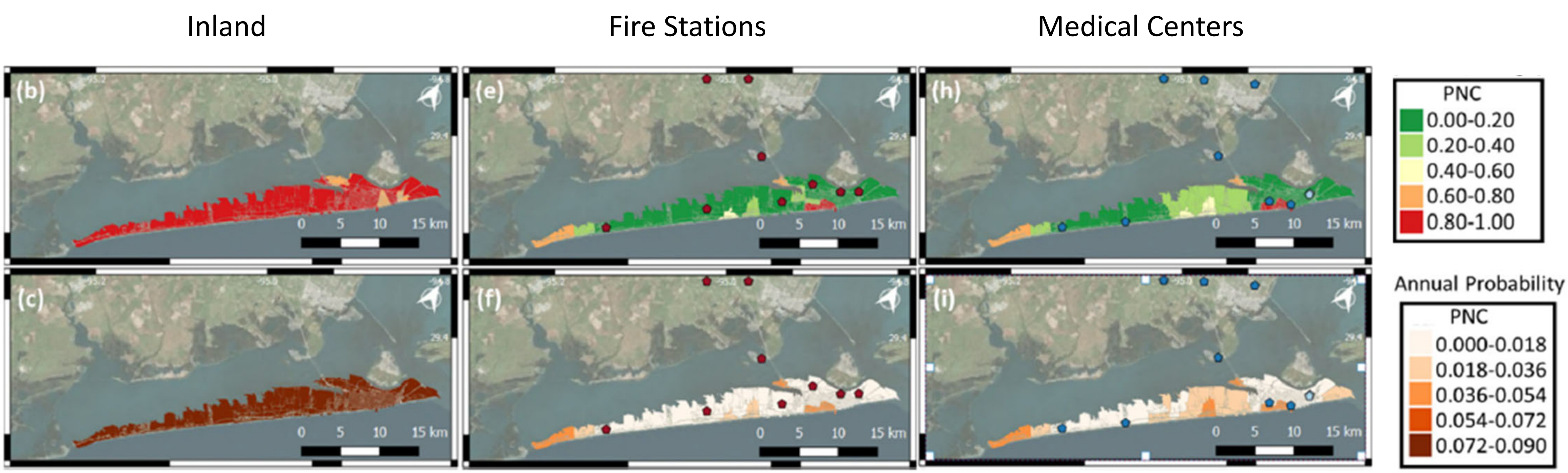
- Recovery is prioritized based on the importance of the component in the overall connectivity of the transportation network.
- The number of available crews for roadway and bridge recovery is variable.





Connectivity to Emergency Services

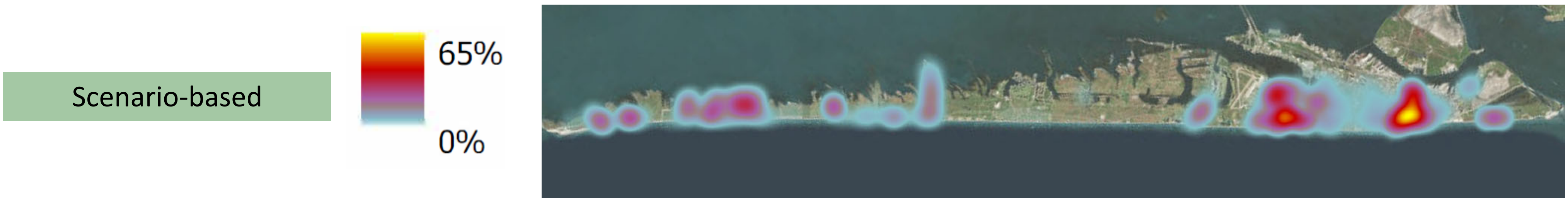
- Probability of disconnection of households from emergency services

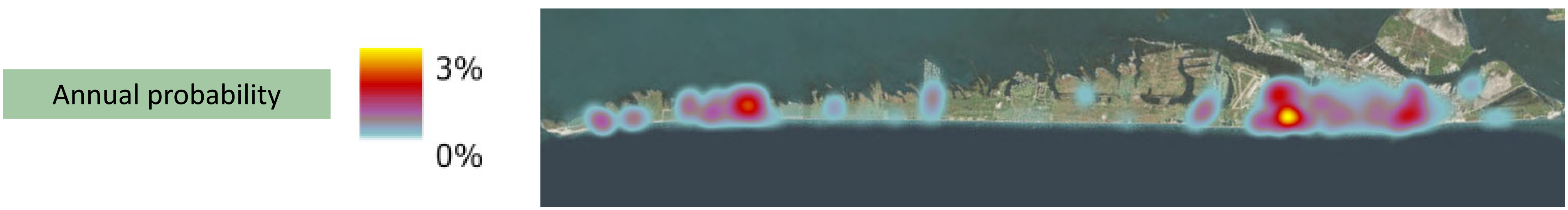


Hybrid Social-Physical Metrics

- Integrated physical/social performance metrics

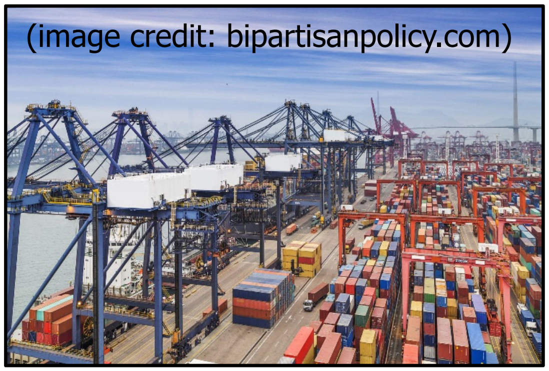
Probability of households being hot: 1) Damaged 2) Non-evacuees inside, and 3) Disconnected from emergency/medical services



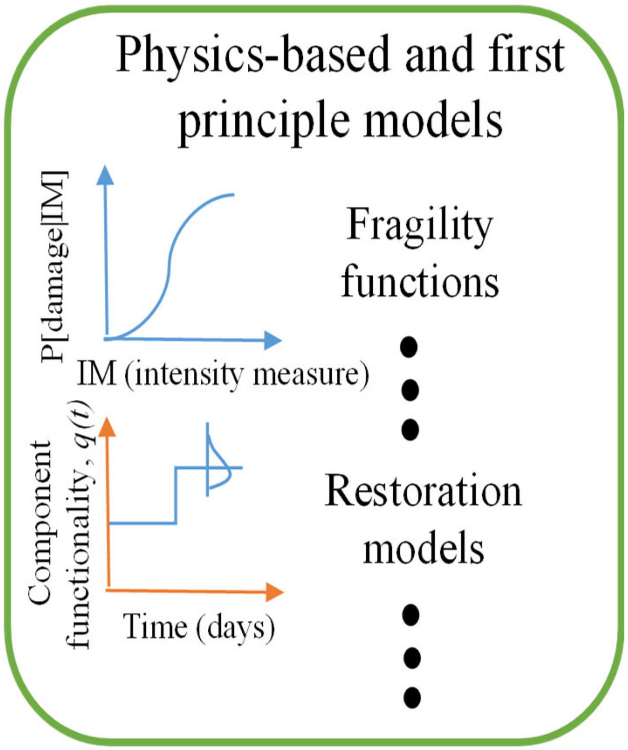


Conclusions, Challenges and Opportunities

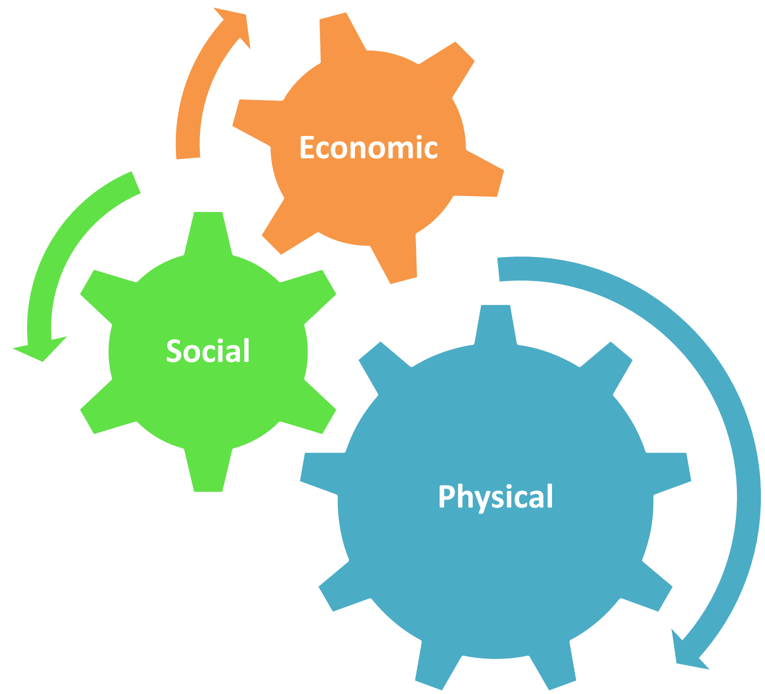
Address Fragility and Restoration Knowledge Gaps


(image credit: bipartisanpolicy.com)


(image credit: abc.net.au)



Enhance Systems Analysis and Coupling



Conclusions, Challenges and Opportunities

Pursue “Smart Resilience”

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

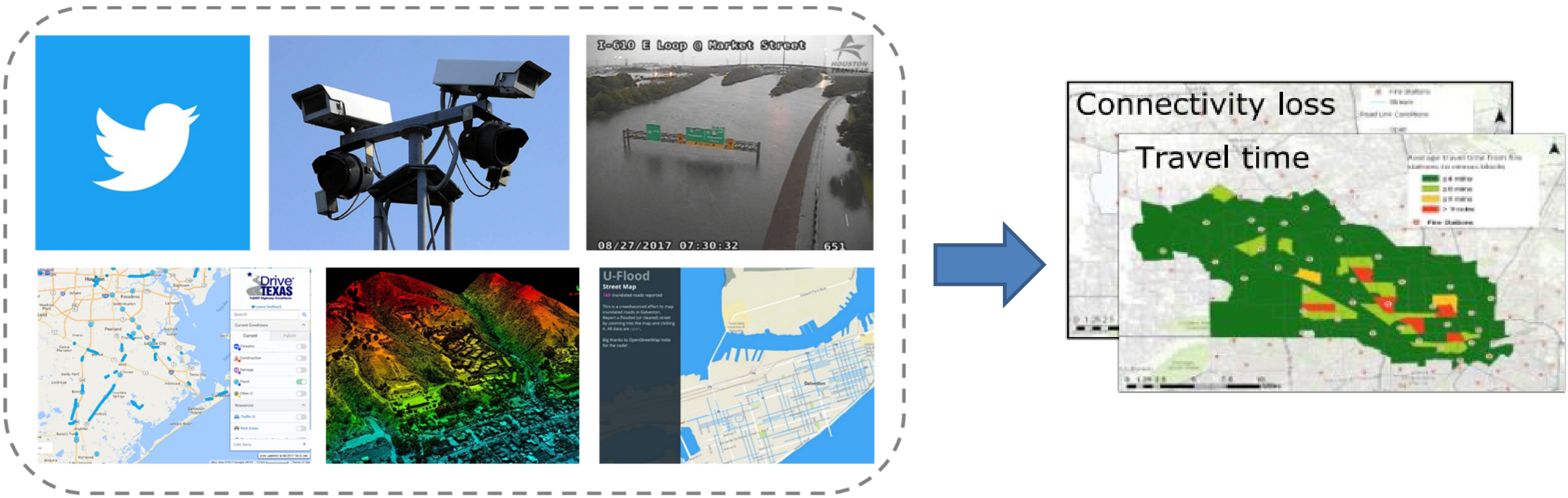


Figure 1. Data sources informing Smart Situational Awareness of Flood impacts on Transportation infrastructure (SSAFT).

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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

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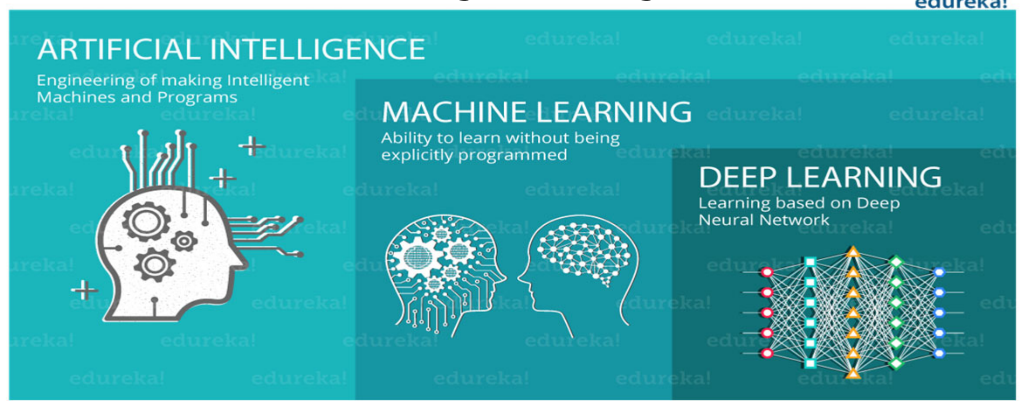
edureka!



Bakshi, A. (2019) What is deep learning? Edurica.co

IN-CORE

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

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Thank you

Acknowledgements

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SSPEED Center

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