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Optimization of Scenario Construction for Loss Estimation in Lifeline Networks

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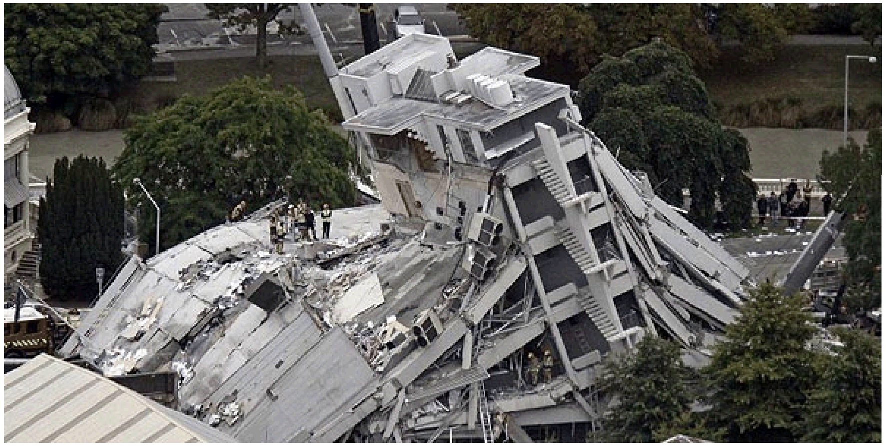
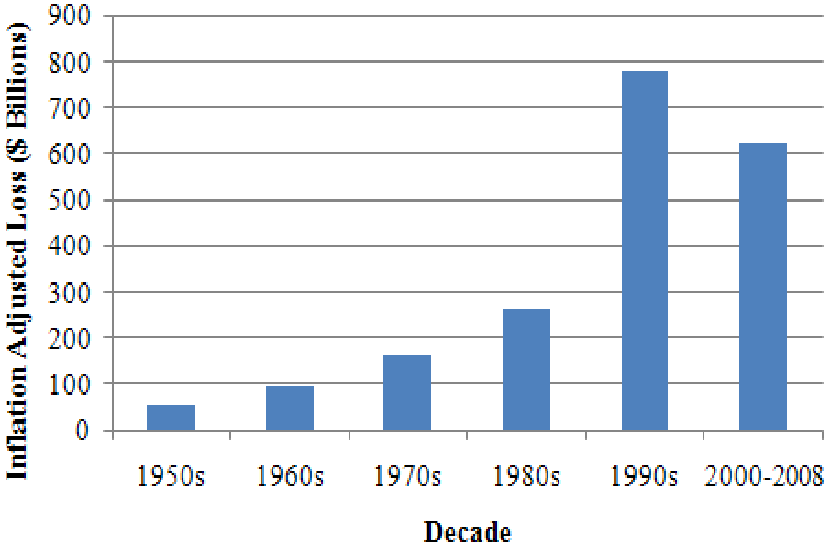
Motivation



2010 New Zealand Earthquake
(7.2 Magnitude)

2010 Haiti Earthquake
(7.0 Magnitude)

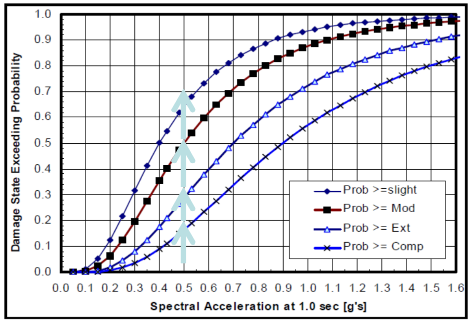
Worldwide Economic Loss by Decade from Natural Disasters*



*Kunreuther, H., E. Michel-Kerjan, N. Doherty, M. Grace, R. Klein, and M. Pauly. 2009. *At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes*. Cambridge: The MIT Press, Cambridge.

Vulnerability of Infrastructure Systems to Earthquake Damage

- Important to be able to estimate the damage to an infrastructure system from an event of interest
  - Great California Shakeout
- Need information on the vulnerability of each component to the event



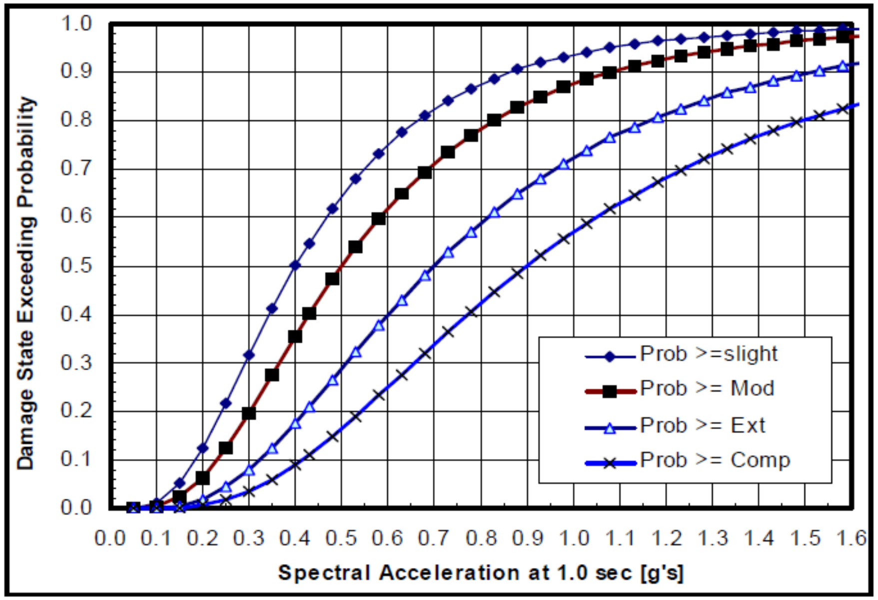
- Need to integrate that information to understand the joint distribution of damage
- Use the joint distribution of system damage to understand the probability distribution for system performance after the event

2011 Earthquake and Tsunami (Fukushima)

1994 Northridge Earthquake

Loss Estimation Methodology

- For a specific event, gives the probability that each component suffers a specific level of damage
- FEMA's HAZUS is a standard methodology
  - Provides fragility curves for infrastructure elements
  - Five damage levels:
    - None
    - Slight
    - Moderate
    - Extensive
    - Complete



Fragility curves for a non-California highway bridge built prior to 1990 of conventional design with length >150 m

Loss Estimation Methodology

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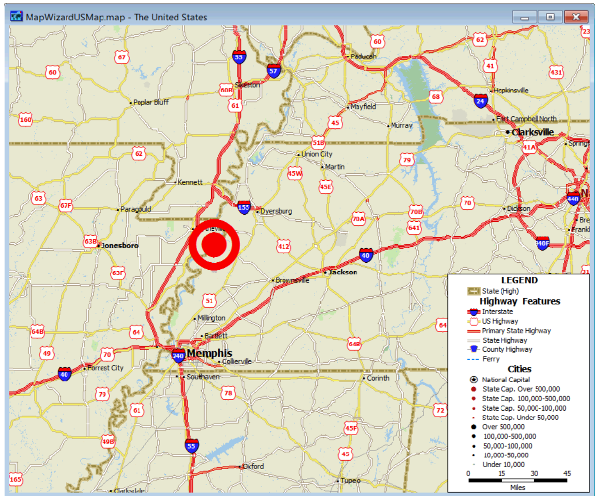
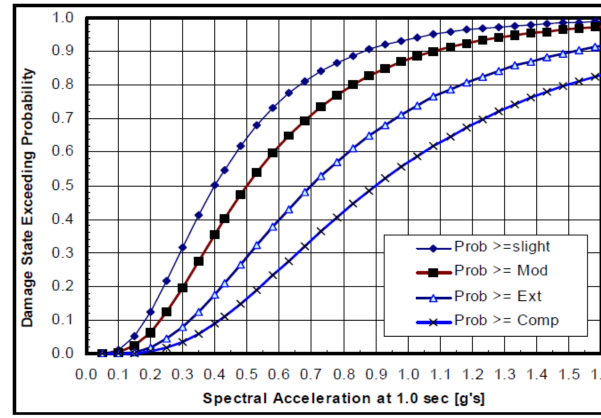
Specific Earthquake Event

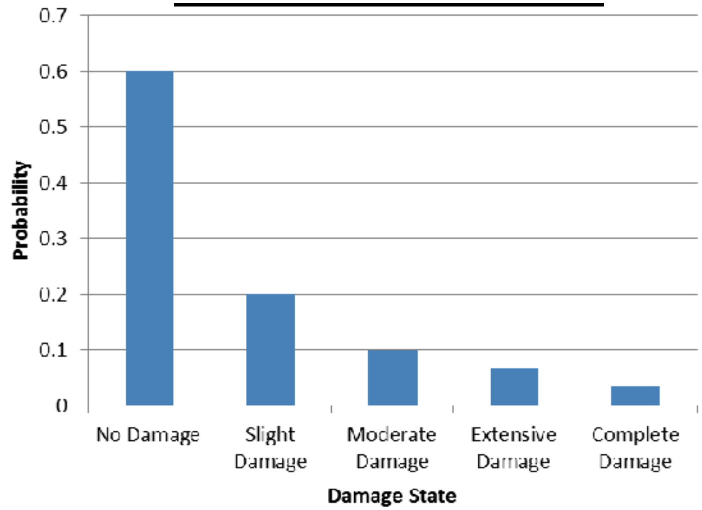


Spectral Acceleration at Bridge Location

Fragility Curves



PMF of Bridge Damage for the Event of Interest



Consequence Scenarios

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Scenario Outcome

Bridge: 1,…*K*

Damage State: 1,…*D*

Scenario: 1,…*J*

Scenario 1	**1**	**2**	**3**	**…**	**k**
None	X				
Slight			X		
Moderate					
Extensive		X			
Complete					X

$$b_{jkd} \in \{0,1\} \quad \forall j,k,d$$

Scenario Probability

Scenario	**Probability**
1	0.3
2	0.2
3	0.15
…	
J	0.1
Total	1.0

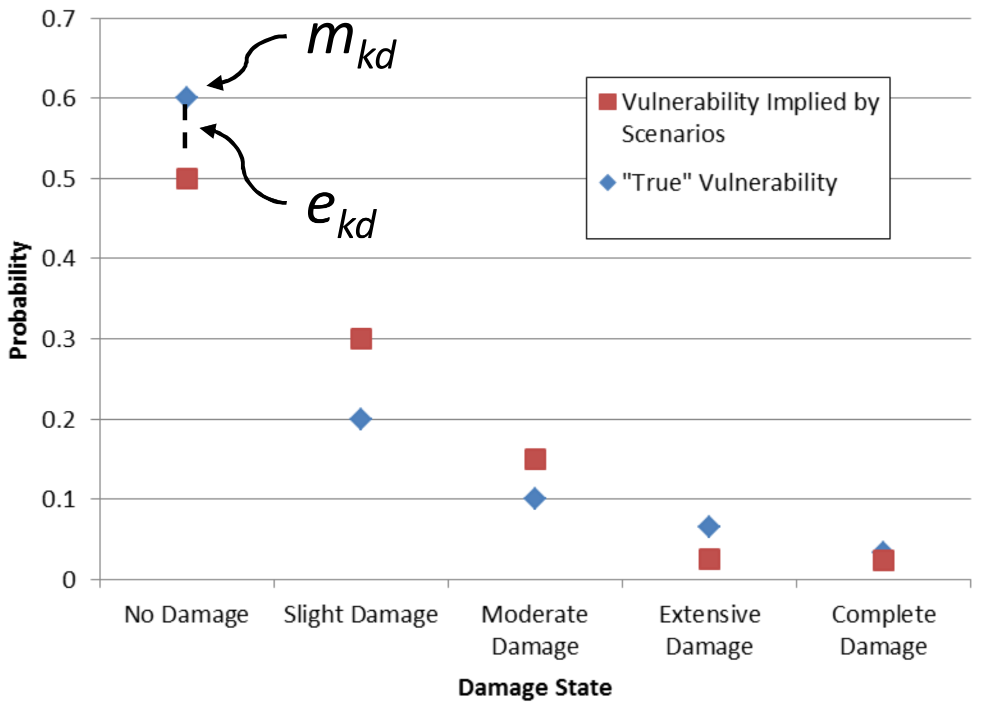
$$0 \leq s_j \leq 1$$

Consequence Scenario Creation

- Common strategy for creating consequence scenarios is Monte Carlo Simulation
  - Çağnan, Z., R. Davidson, and S. Guikema. 2006. “Post-Earthquake Restoration Planning for Los Angeles Electric Power.” *Earthquake Spectra* 22(3):1-20.
  - Jayaram, N., and J. Baker. 2010. “Efficient Sampling and Data Reduction Techniques for Probabilistic Seismic Lifeline Risk Assessment.” *Earthquake Engineering and Structural Dynamics* 39:1109-1131.
  - Chang, S., M. Shinozuka, and J. Moore. 2000. “Probabilistic Earthquake Scenarios: Extending Risk Analysis Methodologies to Spatially Distributed Systems.” *Earthquake Spectra* 16(3):557-572.
- Follow-on analysis typically limits the sample size
  - Computational calculations intensive for each scenario
  - Many iterations are required to determine mitigation strategies
- Accuracy of consequence scenarios sacrificed due to computational limits

Approach

- Use optimization to identify a set of scenarios and the probability of occurrence for each that “match” marginal distribution of damage for each component
- Use these results as input in an infrastructure model to assess system performance



Formulation

Binary
Float
Constant

$$\min \sum_{kd} (e_{kd}^{+} + e_{kd}^{-})$$

Amount that the synthesized scenarios over (under) estimate the probability that bride k is in damage state d

$$\sum_{j} s_j b_{jkd} - e_{kd}^{+} + e_{kd}^{-} = m_{kd} \quad \forall k, d$$

Probability of the j^th scenario

1 if bridge k is in the damage state d in the j^th scenario

Probability that bridge k is in damage scenario d from

Solution procedure

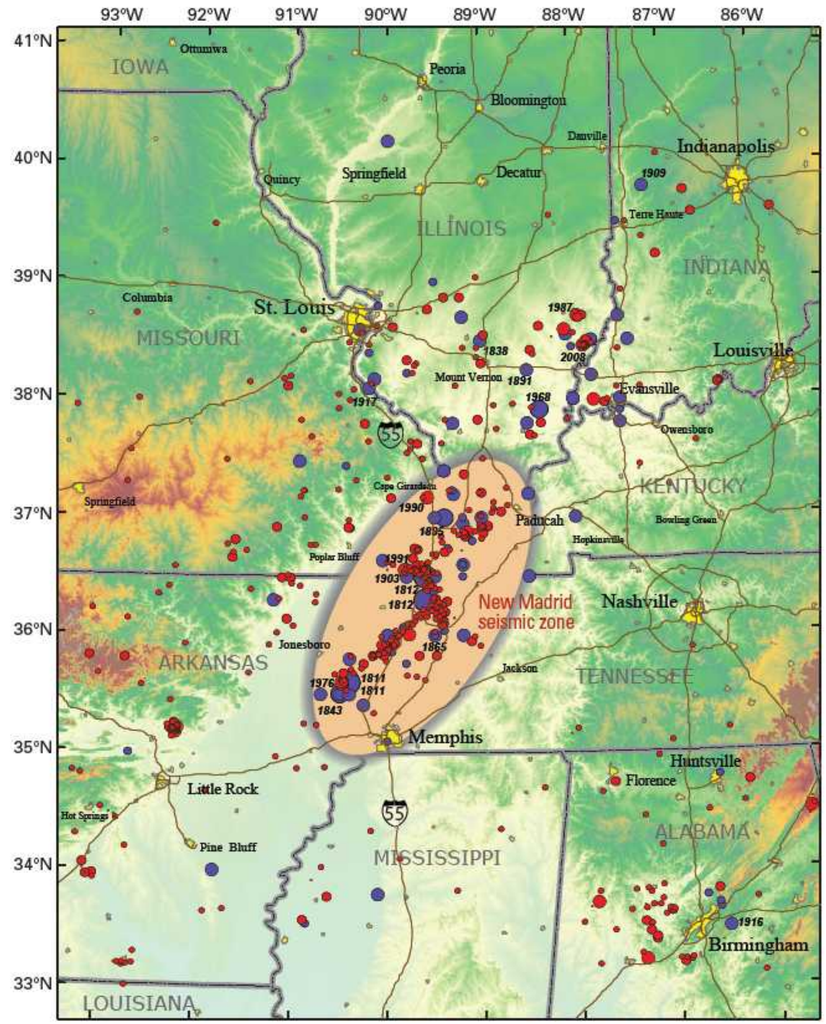
Binary
Float
Constant

$$\min \sum_{kd} \left({e_{kd}}^{+} + {e_{kd}}^{-} \right)$$

$$\sum_{j} s_j b_{jkd} - {e_{kd}}^{+} + {e_{kd}}^{-} = m_{kd} \quad \forall k, d$$

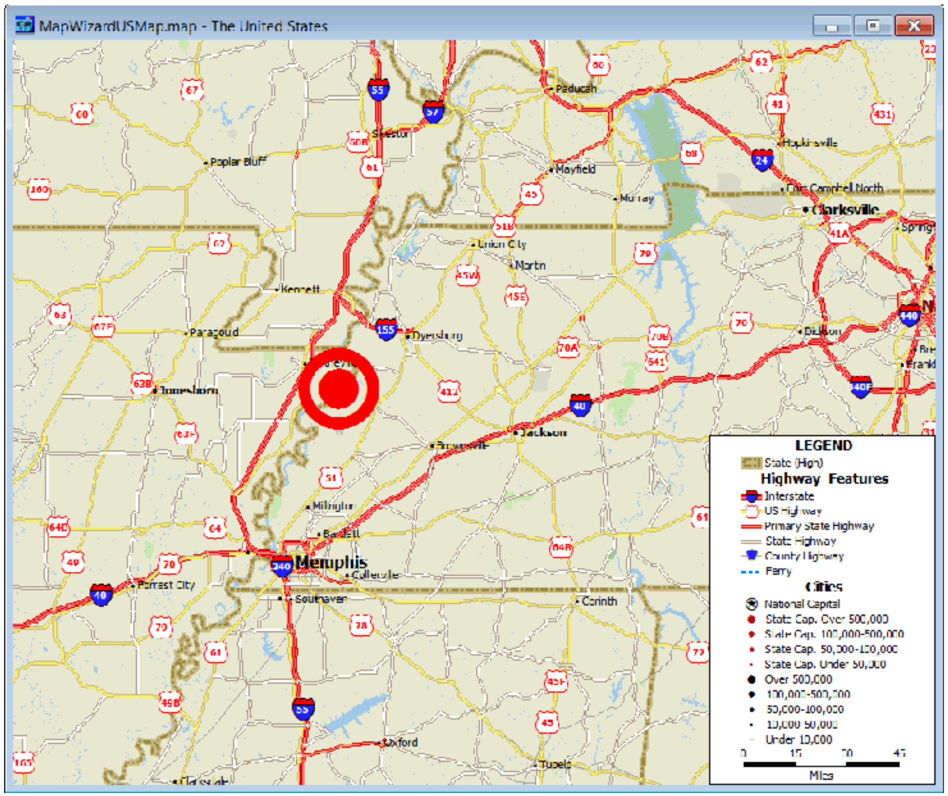
- If s_j is known, formulation is a mixed-integer linear program that decomposes by bridge
- If b_{jkd} is known, formulation is a linear program
- Iterative procedure of solve
  - Assume all scenario are equally likely (1/J)
  - Solve the resulting mixed-integer linear program for b_{jkd} for each bridge
  - Assume the values for b_{jkd} and solve for s_j
  - Objective is non-decreasing hence, iterate until no improvement in objective

Case Study: New Madrid Seismic Zone

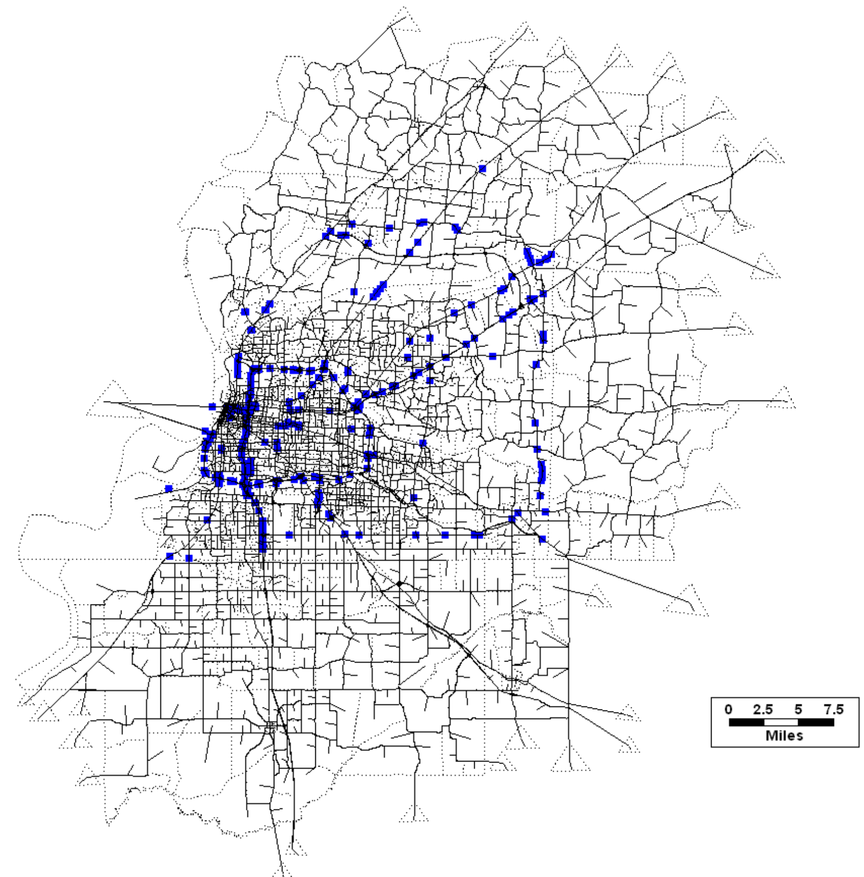


Case Study: Memphis Highway Network

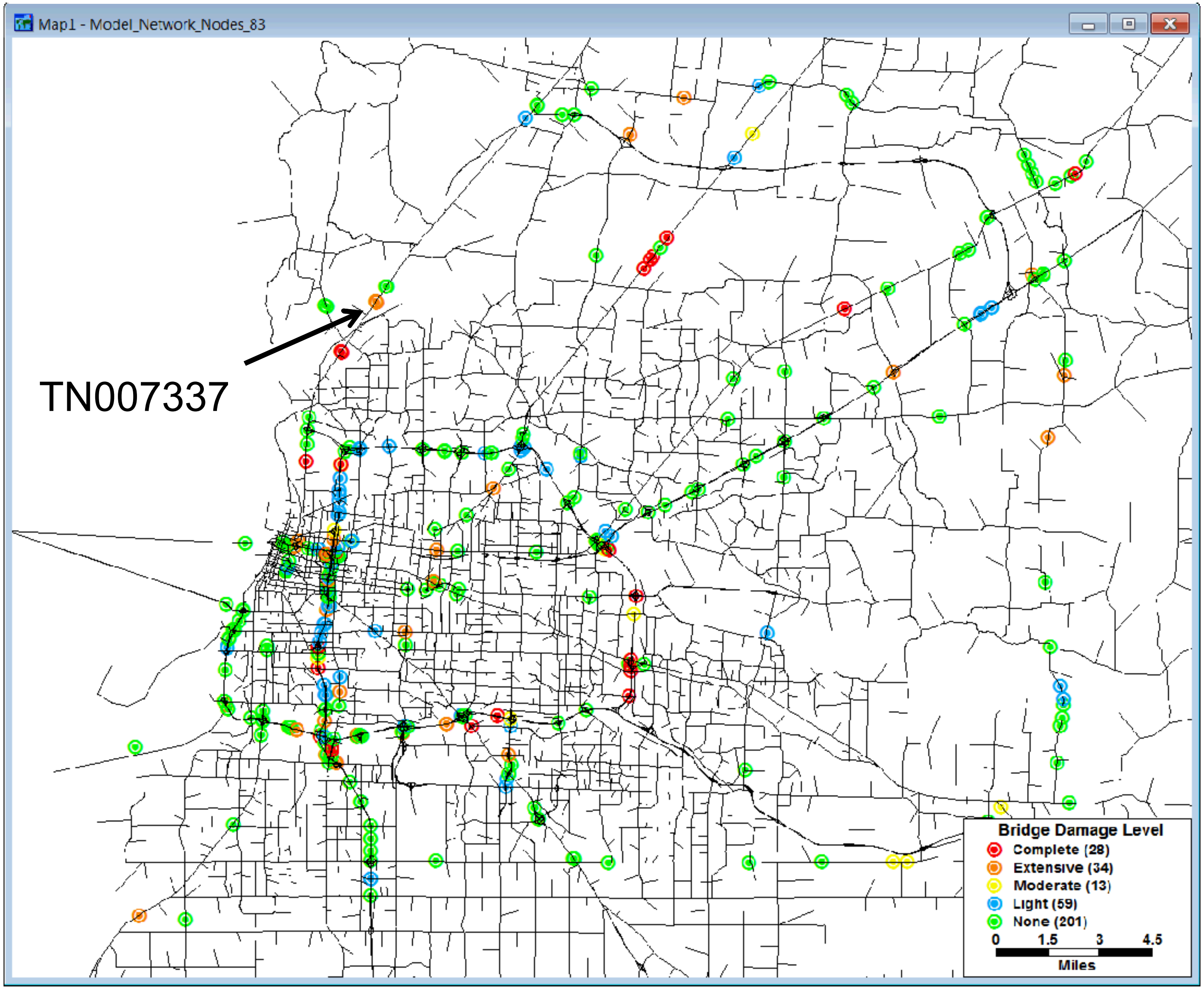
Event: 7.7 moment of magnitude earthquake on the Mississippi River between Kentucky and Mississippi



Infrastructure: 335 bridges on the Memphis Metropolitan Area's highway network



Result: Scenario 1 of 9

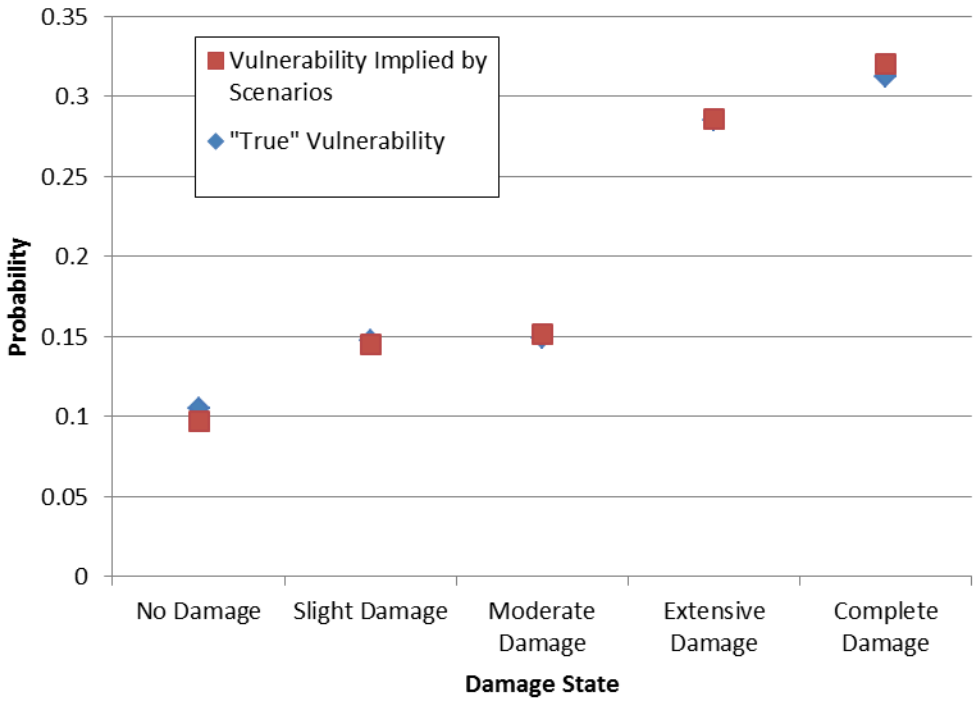


Results: Bridge TN007337

Model Output with 9 Scenarios

Scenario	Probability	Damage (Bridge TN007337)
1	0.12	Extensive
2	0.11	Moderate
3	0.10	None
4	0.13	Complete
5	0.04	Moderate
6	0.15	Light
7	0.17	Extensive
8	0.07	Complete
9	0.12	Complete

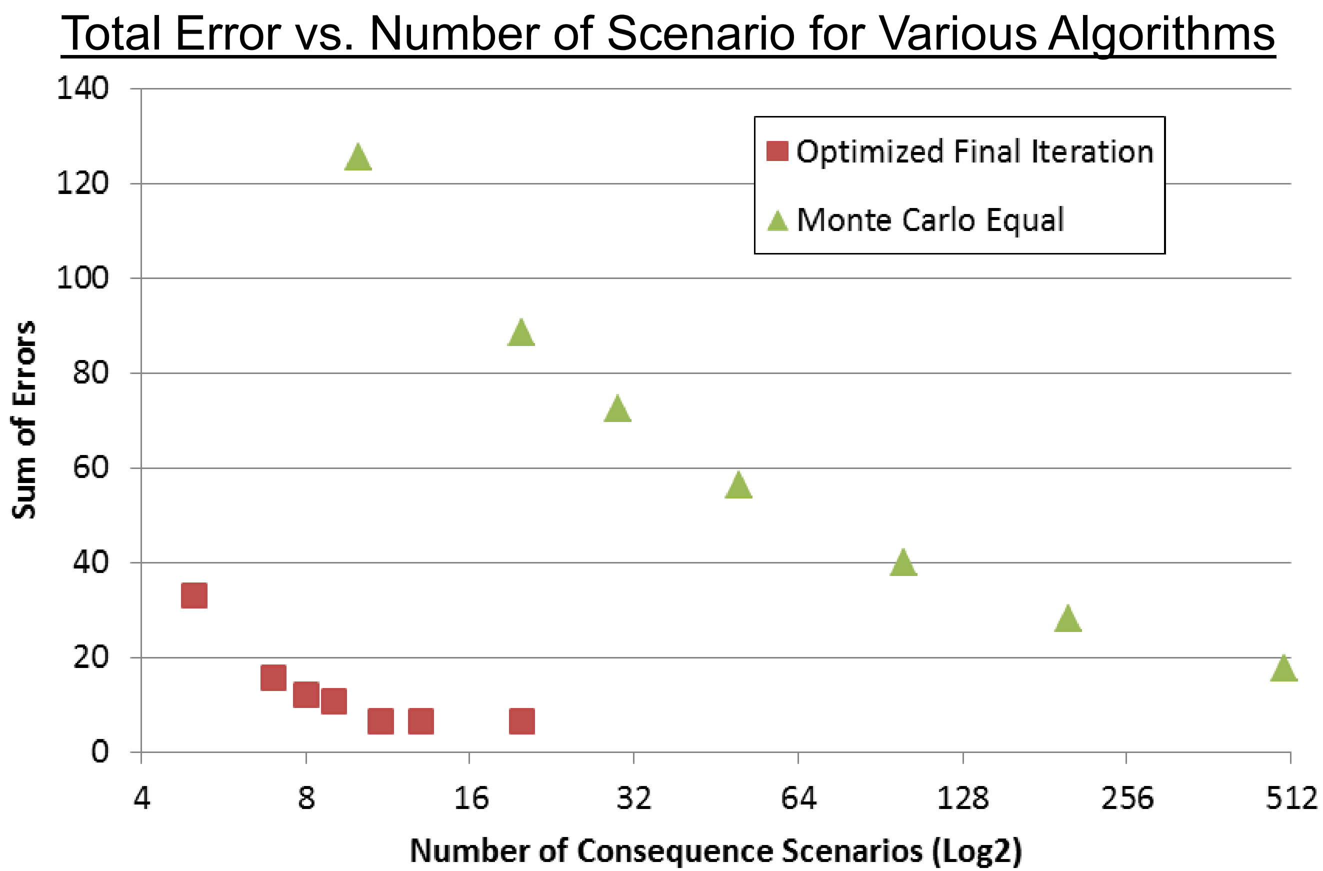
"True" vs. Implied Vulnerability for Bridge TN007337



Absolute deviation of 0.02 across all damage states for bridge TN007337

Deviations From "True" Vulnerability

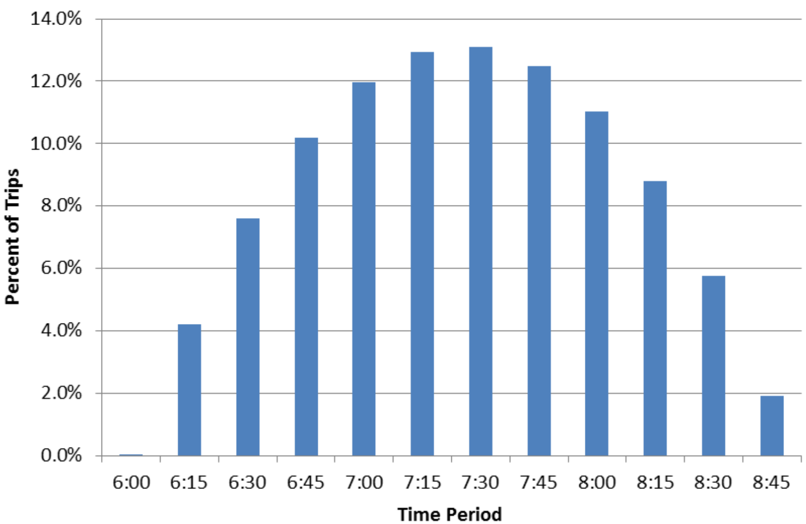
- Sum of the errors over all bridges and damage states (objective function)



Impact to Highway Network

- Measure increase in travel time due to bridge damage
- Dynamic Traffic Assignment (DTA) Algorithm
  - Users dynamically select the route that minimized their travel time
  - Generalization of user equilibrium
- Interested in the AM peak period (6AM-9AM); 560,000 trips

Trips by Time Period (AM Peak)

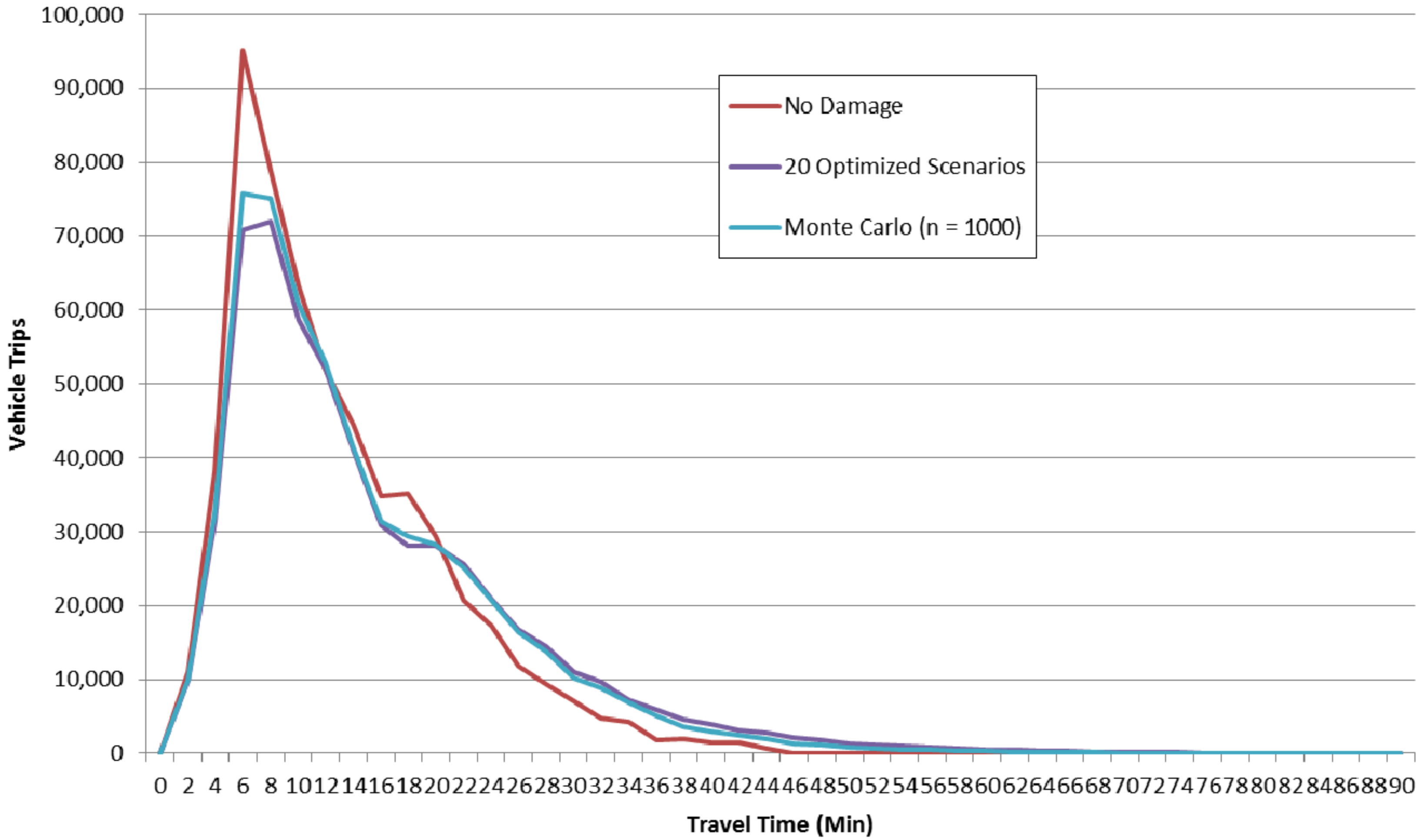


Damage Level to Traffic Capacity Mapping

Damage Level	Roadway Capacity On Bridge	Roadway Capacity Under Bridge
None	100%	100%
Slight	100%	50%
Moderate	0%	0%
Extensive	0%	0%
Complete	0%	0%

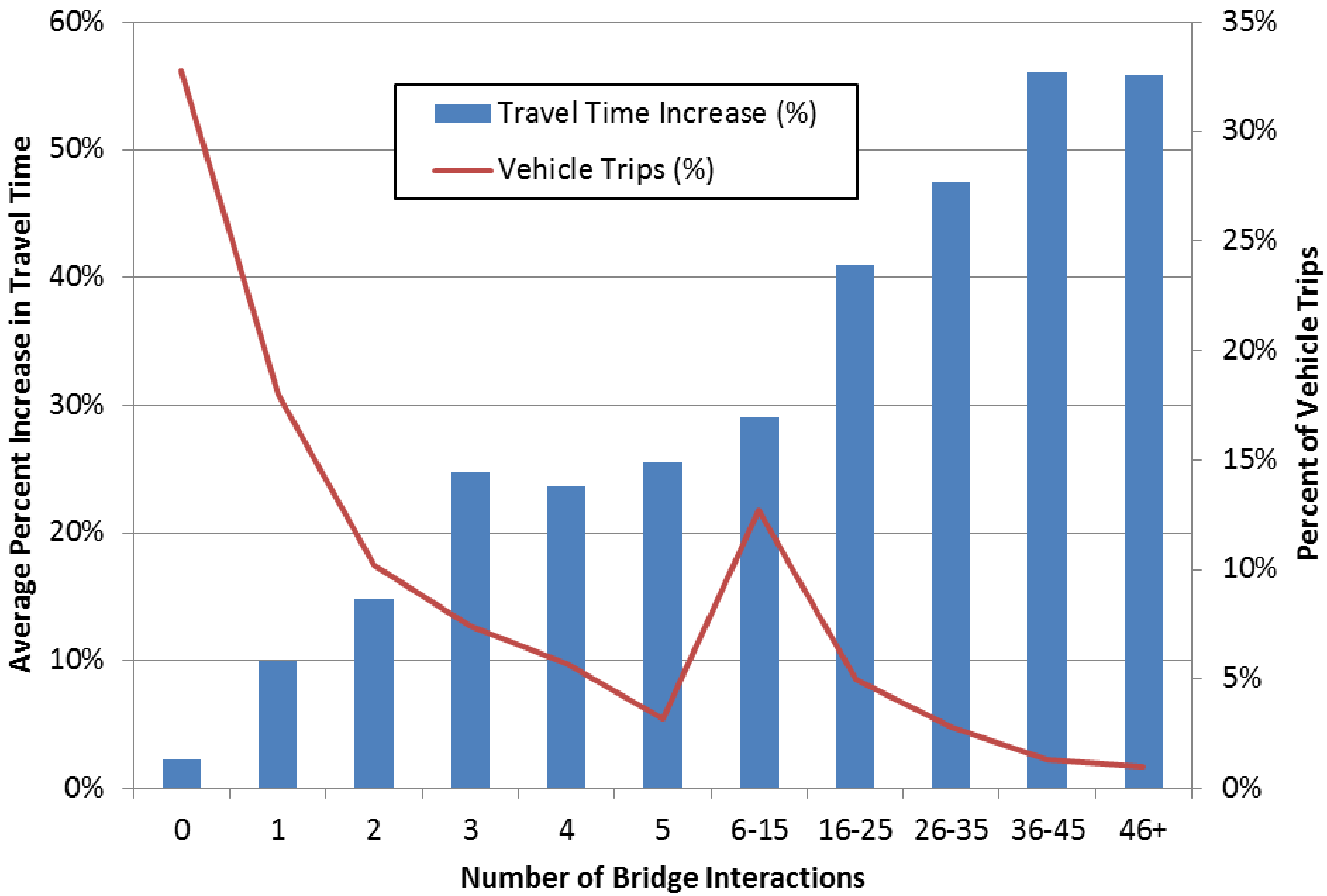
DTA Results

Histogram of Vehicle Travel Times for Various Damage Scenarios

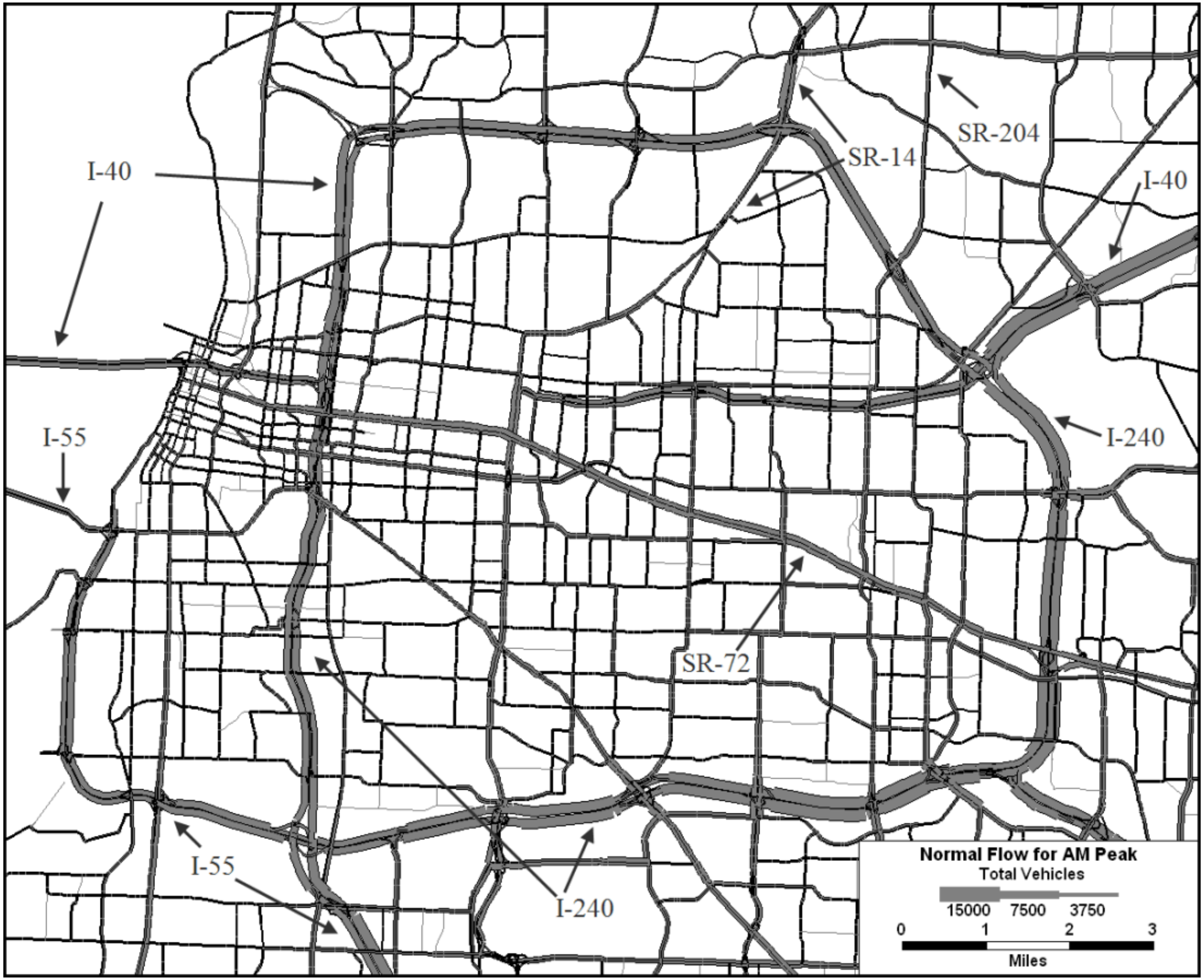


DTA Results

Percent Increase in Travel Time vs. Number of Bridges Crossed



Non-Event AM Volumes



Post Event AM Expected Volumes

Next Steps

- Integrate multiple events into a optimization
  - Provide the model with several events and a total number of consequence scenarios
  - Let the model decide the number of consequence scenarios to assign to each event
- Consequence scenarios by mitigation strategy
  - Infrastructure elements have a fragility curve for each mitigation strategy
  - Create consequence scenarios that minimize errors and provide damage states under all mitigation strategies