Mitigating Hazard Consequences through Optimal Infrastructure Investments

SAND2012-10620P

Nathanael Brown

Jared Gearhart

Sandia National Laboratories

Sandia National Laboratories

Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

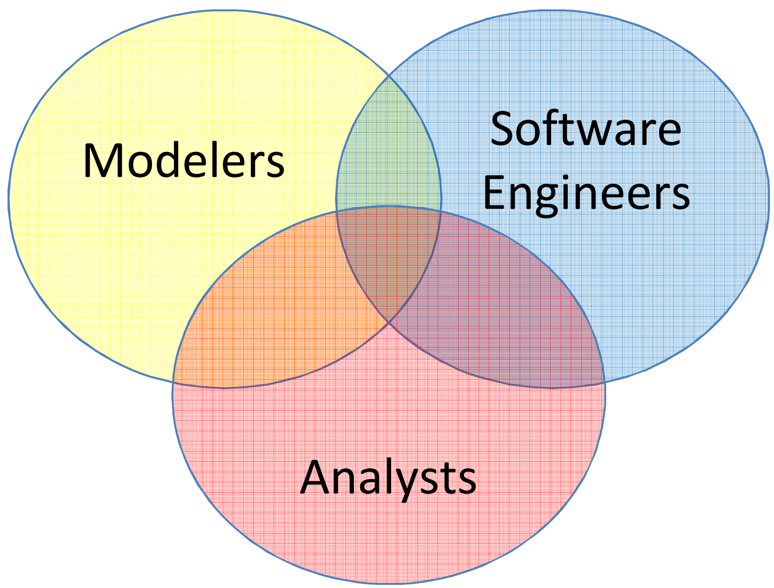
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Overview

- Background
  - Introductions
  - Research activities
  - Mathematical techniques
- Current research
  - Optimizing infrastructure investments
  - Part 1: Efficient modeling of hazards and consequences
  - Part 2: Determining infrastructure performance and optimal investment strategy

Introductions

- Jared Gearhart – Operations Research Analyst
- Nathanael Brown – Software Developer
- Operations Research and Computational Analysis Department
  - Use operations research and computational analysis to address national security issues
  - Focus on application



Modeling Activities

- Research, design, develop, and implement optimization and simulation-based technology across broad set of application domains
  - Transportation
  - Logistics Modeling
  - Critical Infrastructures
  - Process Modeling
- Network analysis incorporates:
  - Physical components and connections
  - Business rules
  - Interdependencies between networks
  - Dynamic nature of system
- Goals:
  - Improve decision making
  - Identify vulnerabilities & disruption impacts
  - Determine efficient use of scarce resources
  - Incorporate uncertainty into "What's Best" analysis

Mathematical Arena

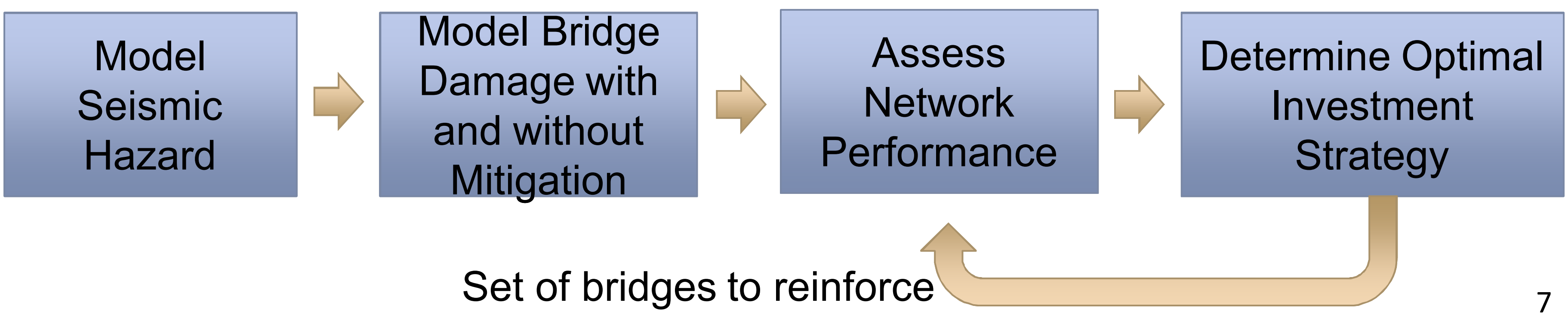
- Mathematical programming & simulation capability
  - Linear Programs (LPs)
  - Mixed Integer Programs (MIPs)
  - Non-linear Programs
  - Discrete-event simulation
  - Heuristics, Genetic Algorithms, etc.
  - Continuous-flow simulation
- Exploiting the benefits of optimization and simulation
  - Optimization under Uncertainty
  - Stochastic Optimization
  - Experience with combining optimization and simulation in application

Current Research

- Goal:
  - Develop an analysis framework for investment planning
  - Multiple hazards
  - Multiple infrastructures
  - Optimal investment strategy
- Motivation:
  - Investments currently done in isolation
  - Decreasing budgets
  - Increasing infrastructure complexity and interdependency
- Computational efficiency is paramount
- Lab Directed Research and Development (LDRD) effort

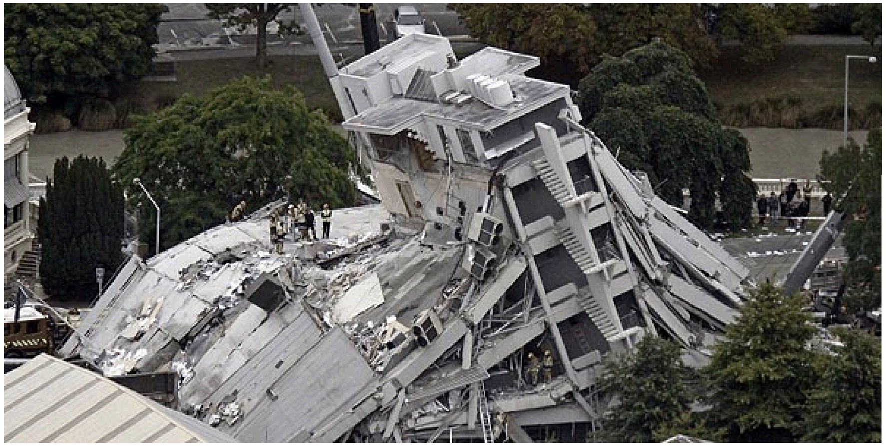
Roadmap

- Case study
  - Region: Memphis, TN metropolitan area
  - Hazard: earthquakes (New Madrid)
  - Infrastructure: highway network
    - Focus on the bridges as the key network vulnerability
    - Post-event performance of network
      - Travel times
      - Hospital connectivity
  - Investment: seismic reinforcement of bridges



Motivation

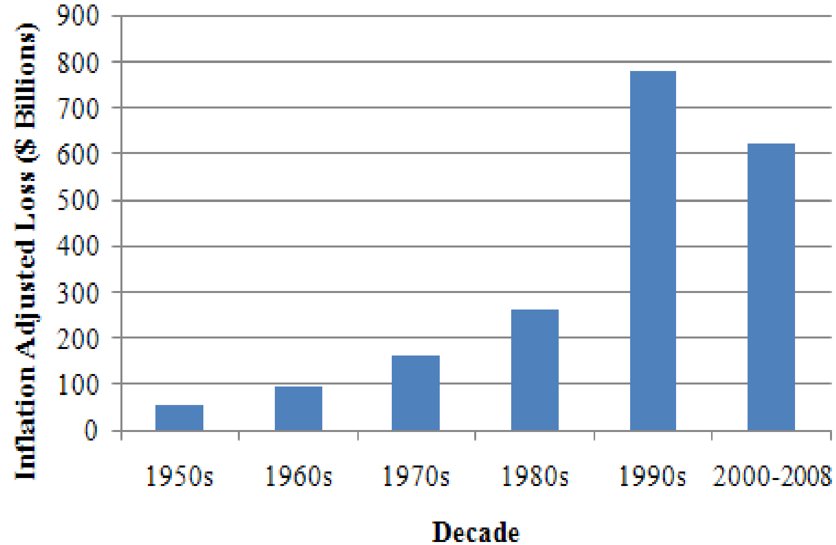
Sandia National Laboratories



2010 New Zealand Earthquake
(7.2 Magnitude)

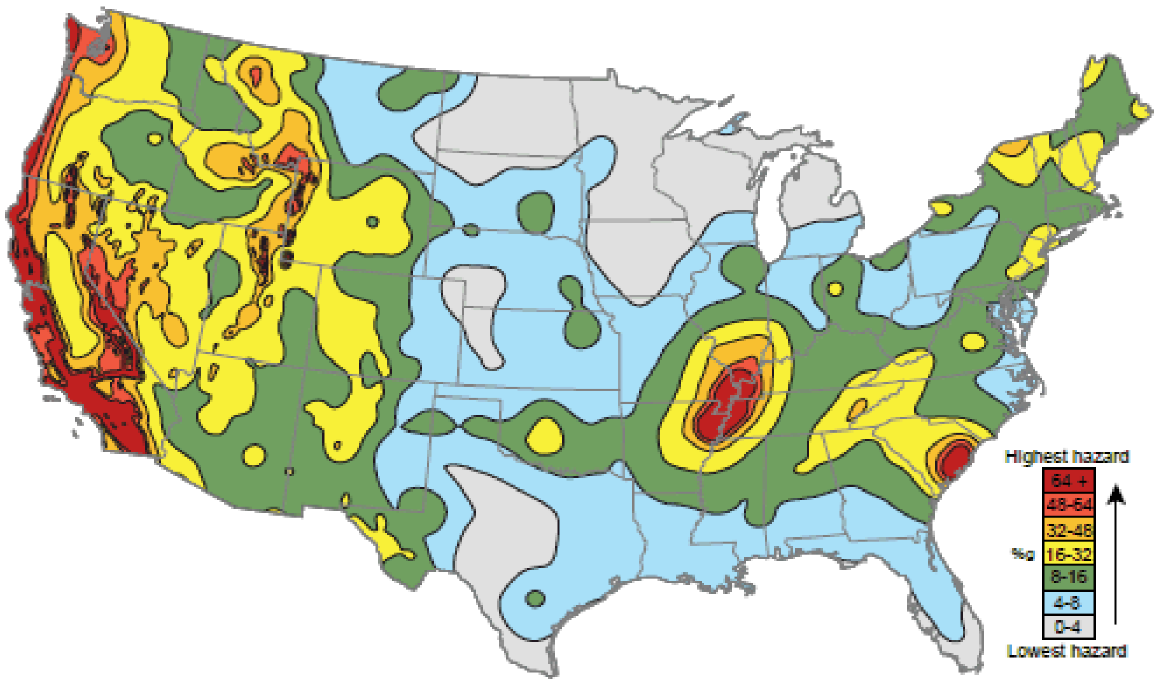
2010 Haiti Earthquake
(7.0 Magnitude)

Worldwide Economic Loss by Decade
from Natural Disasters



Seismic Hazard

- Consider the seismic hazard in the New Madrid Seismic Zone

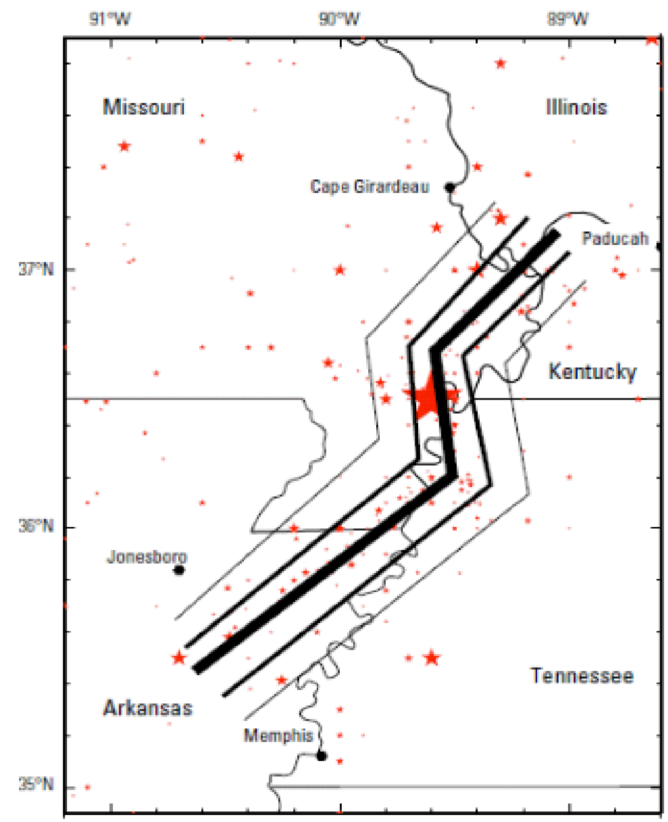


<u>Seismic hazard for the continental US</u>

Peak ground acceleration (PGA) as a percent of gravity
with 2% exceedence probability in 50 years

Representing the Hazard

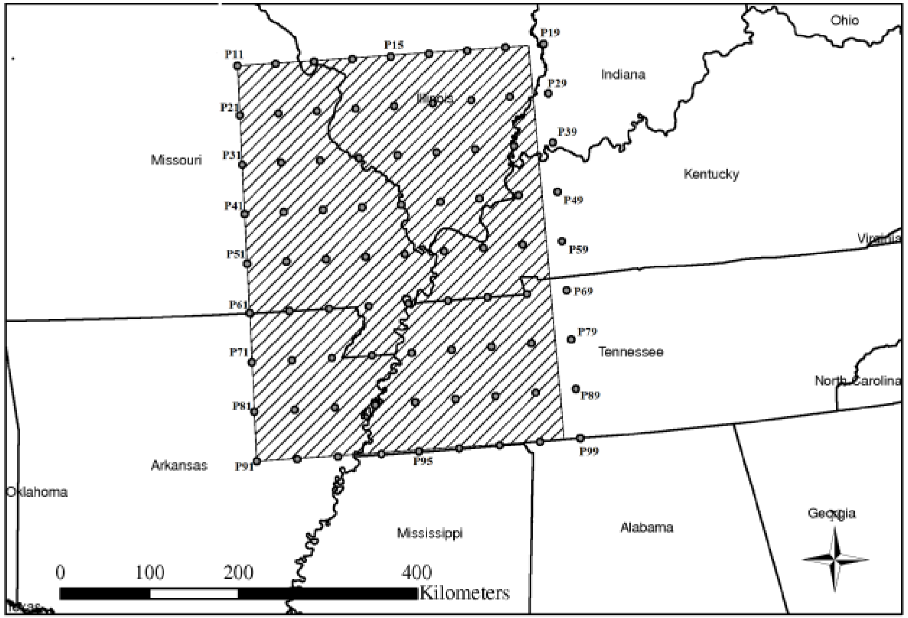
- Analysis requires a collection of earthquake scenarios
- Two sources of candidate earthquake scenarios
  - USGS has cataloged 433 historic events
  - USGS has developed 5 synthetic faults
    - We consider 4 possible magnitudes from each fault (20 total events)
- Computations preclude considering all 453 events
- Can a representative set of events be created?



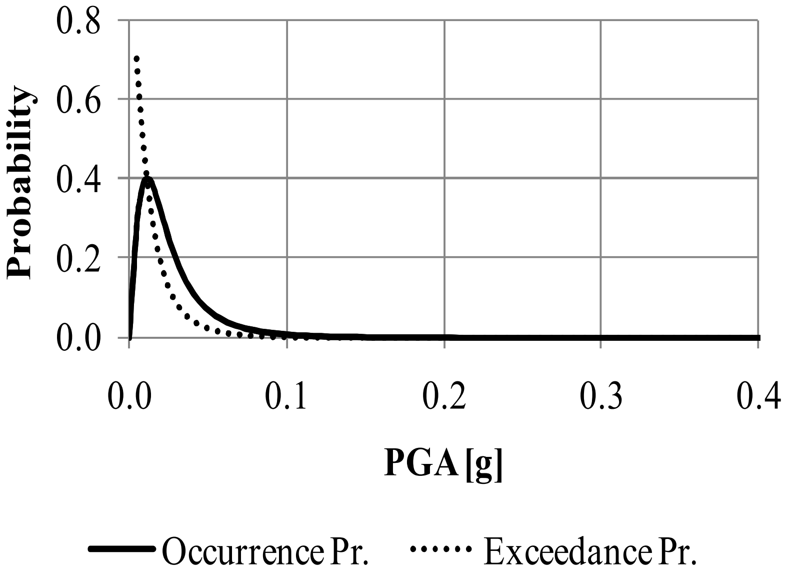
Creating Representative Events

- USGS has created control points and associated assessment of seismic vulnerability
- Seismic models can be used to estimate ground shaking at control points for a given event

<u>81 USGS Control Points</u>



<u>PGA for P35 for 5.1 Magnitude Event (Lat: 38.0, Lon: -89.5)</u>



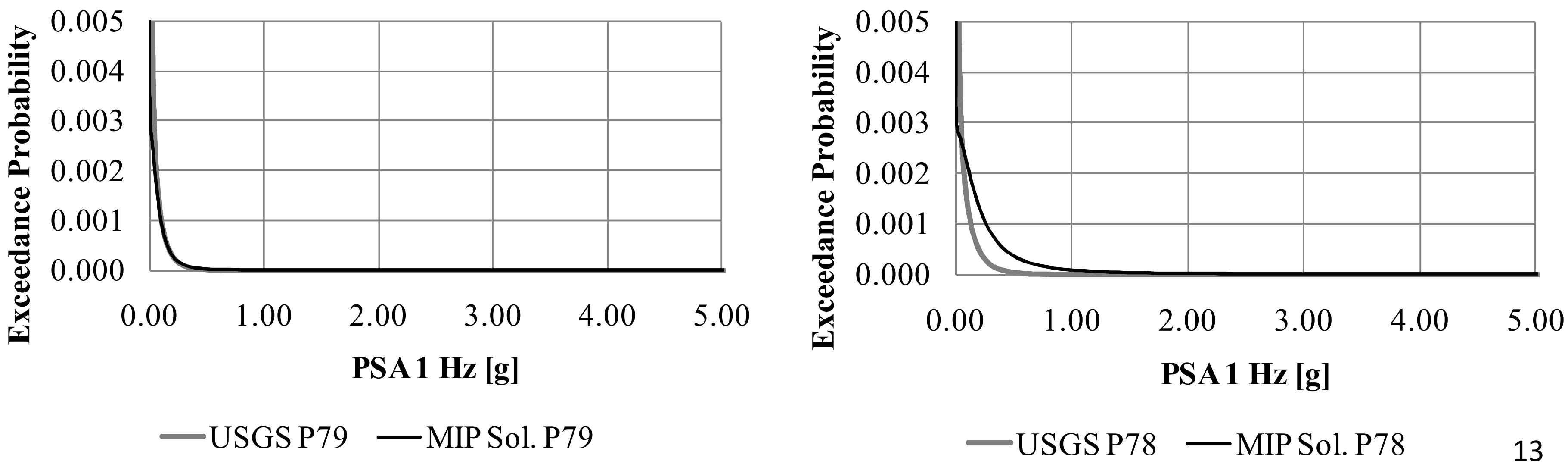
Creating Representative Events

- Formulate a math program to select a set of representative earthquake events
- Goal: select a subset of the 453 earthquake events each with an associated weight whose implied ground shaking matches the expected ground shaking at each control point as closely as possible

Event Selection Results

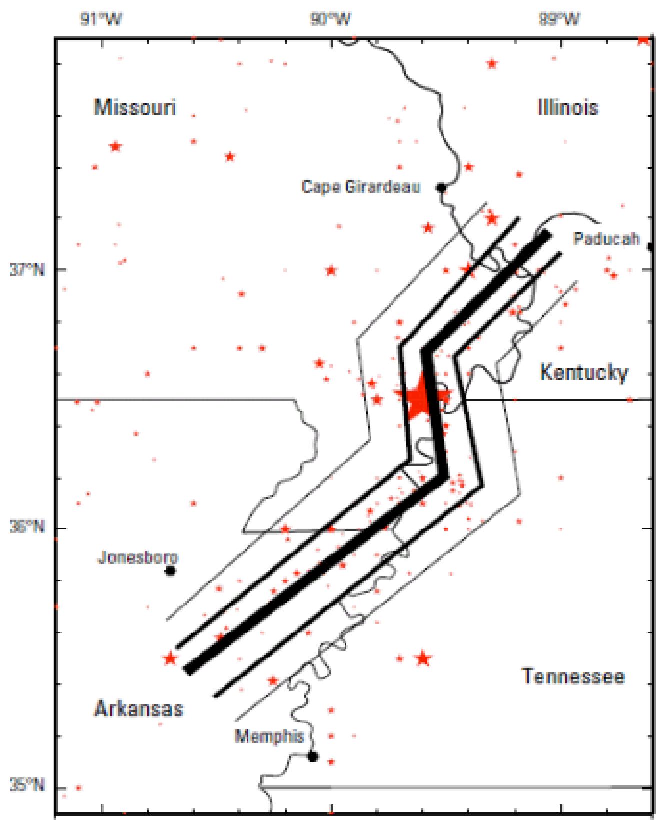
- No more than eight events
- Most control point matched closely in both cases
- Larger deviations occurred for several control points

Expected and Implied Exceedence Curves for Two Control Points

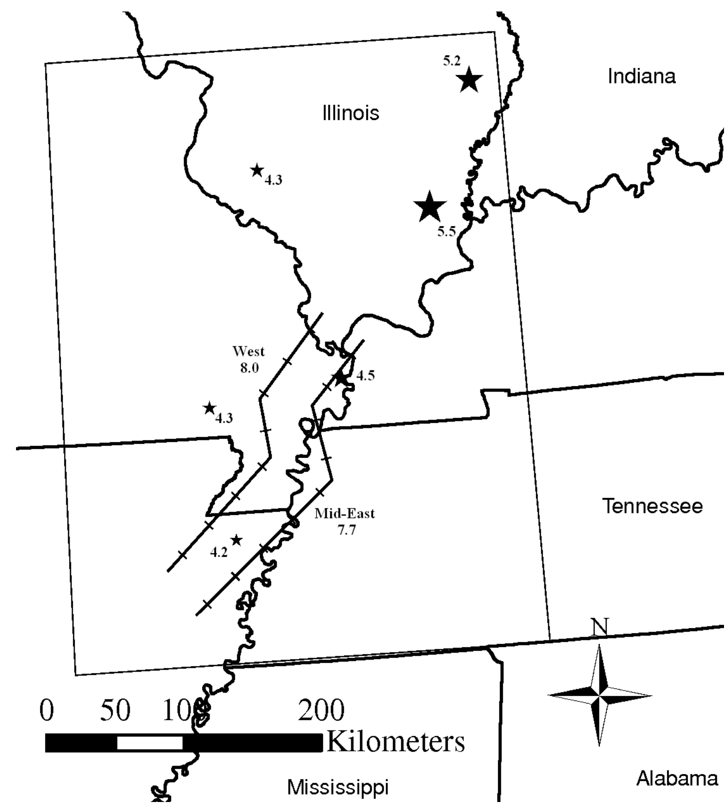


Event Selection Results

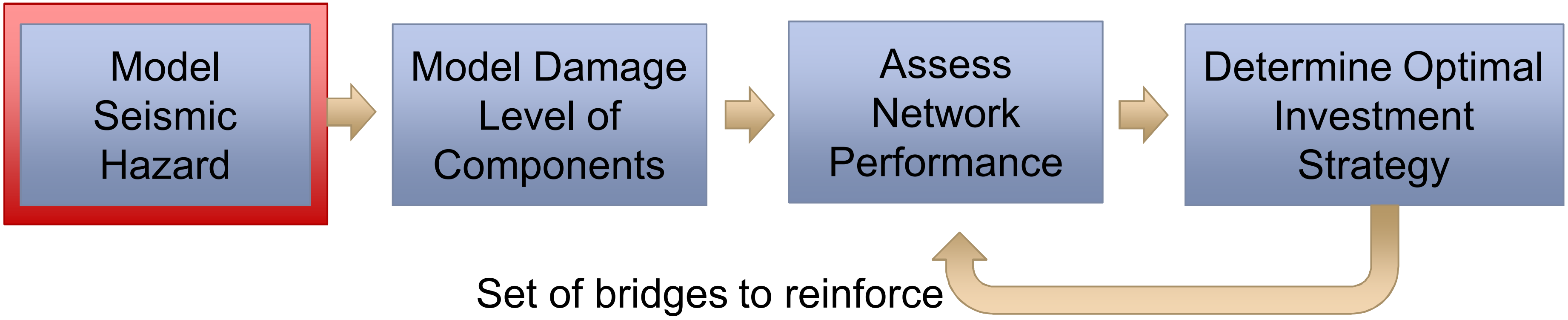
Complete Set of 453 Events



8 Events Selected through Optimization



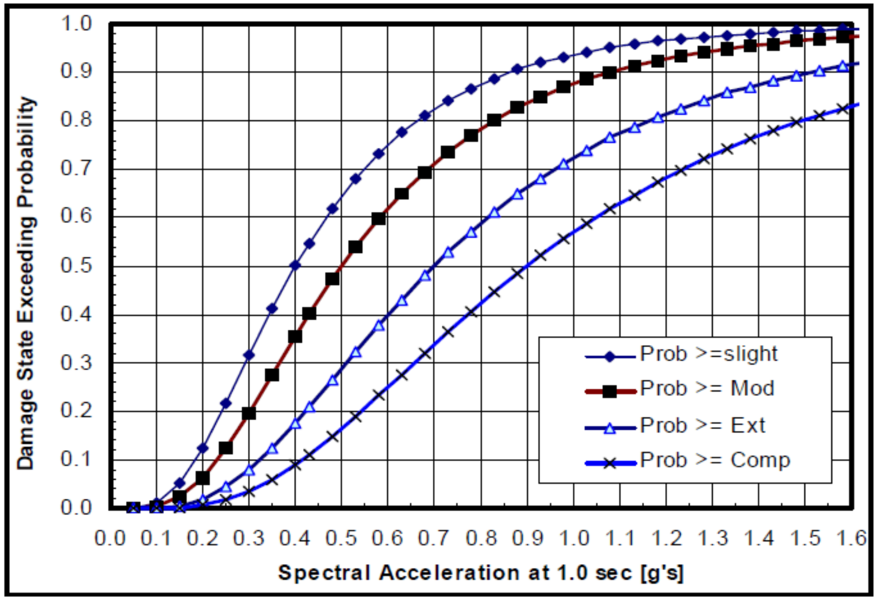
Roadmap



- Previous method allowed for the creation of a representative set of earthquake events
- Next we use representative earthquakes to model damage to highway network components (bridges)

Loss Estimation Methodology

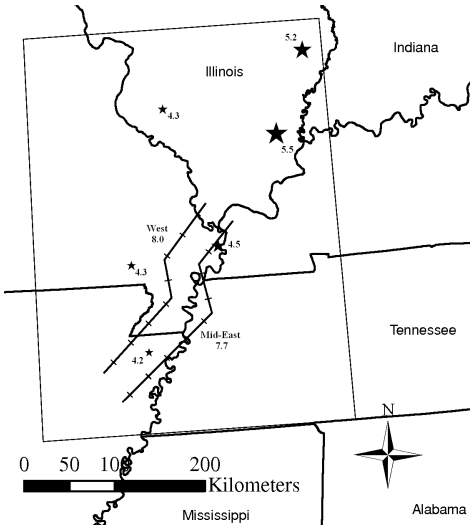
- For a specific event, gives the probability that each component suffers a specific level of damage
- FEMA's HAZUS is a standard methodology
  - Provides fragility curves for infrastructure elements
  - Five damage levels:
    - None
    - Slight
    - Moderate
    - Extensive
    - Complete



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

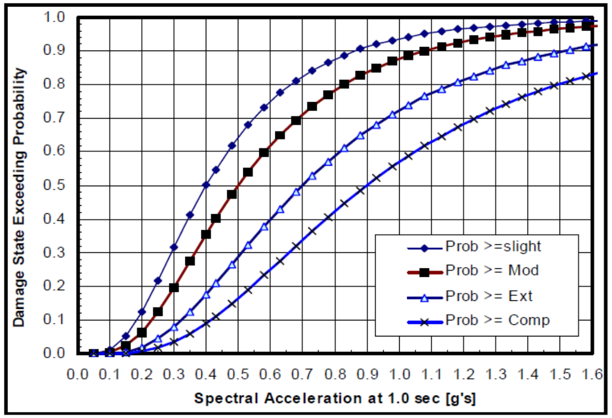
Loss Estimation Methodology

Specific Earthquake Event

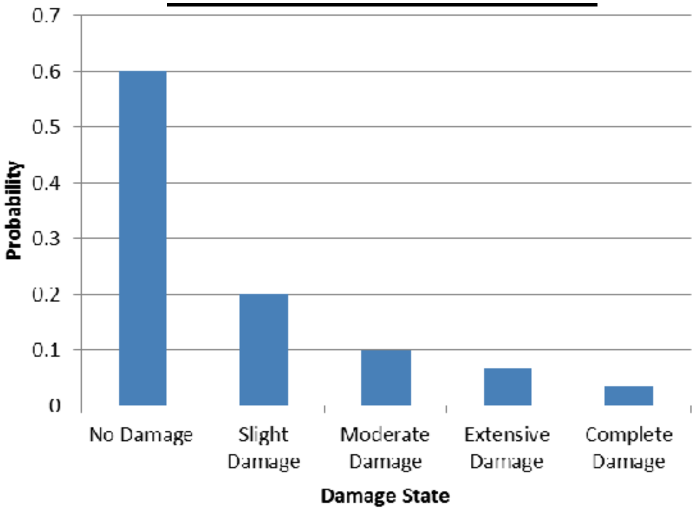


Spectral Acceleration at Bridge Location

Fragility Curves



PMF of Bridge Damage for the Event of Interest



Consequence Scenarios

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

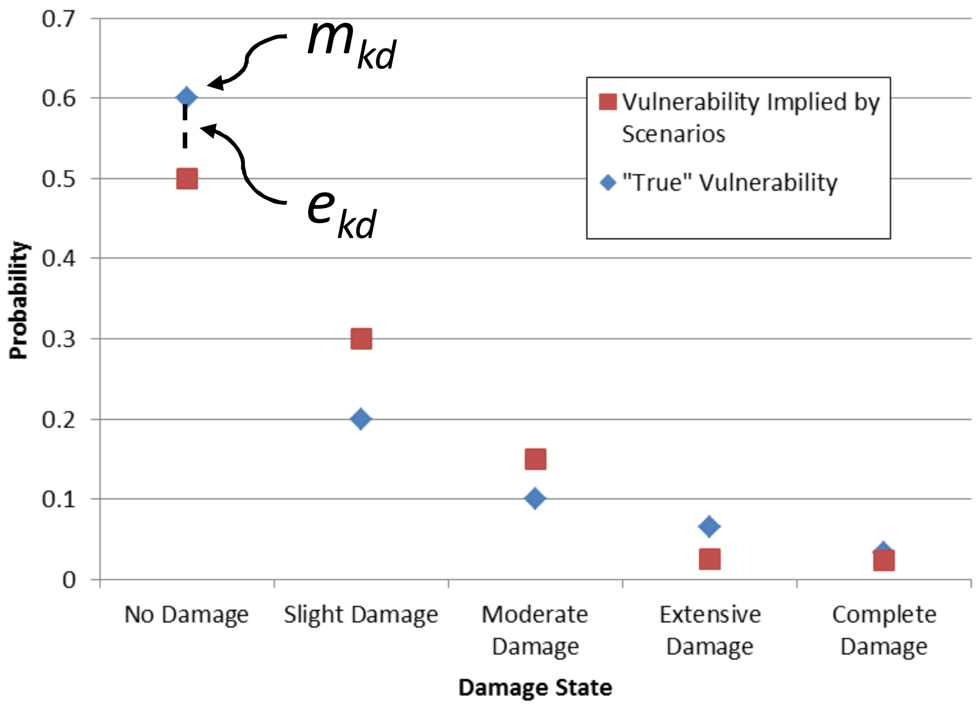
$$0 \leq s_j \leq 1$$

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 and the correlation between components



Formulation

Binary
Float
Constant

$$\min \sum_{kd} e_{kd}{}^2 + \sum_{kk'} \delta_{kk'}{}^2$$

$$\sum_j s_j b_{jkd} - e_{kd} = m_{kd} \quad \forall k, d$$

Implied Vulnerability/ Covariance

Error Term

"True" Vulnerability/ Covariance

$$\sum_j \sum_{d,d'} \left(b_{jkd} - \sum_j b_{jkd} s_j\right)\left(b_{jk'd'} - \sum_j b_{jk'd'} s_j\right) s_j + \varsigma_{kk'} = \sigma_{kk'} \quad \forall k \neq k'$$

Solution procedure

Binary
Float
Constant

$$min \sum_{kd} e_{kd}{}^2 + \sum_{kk'} \delta_{kk'}{}^2$$

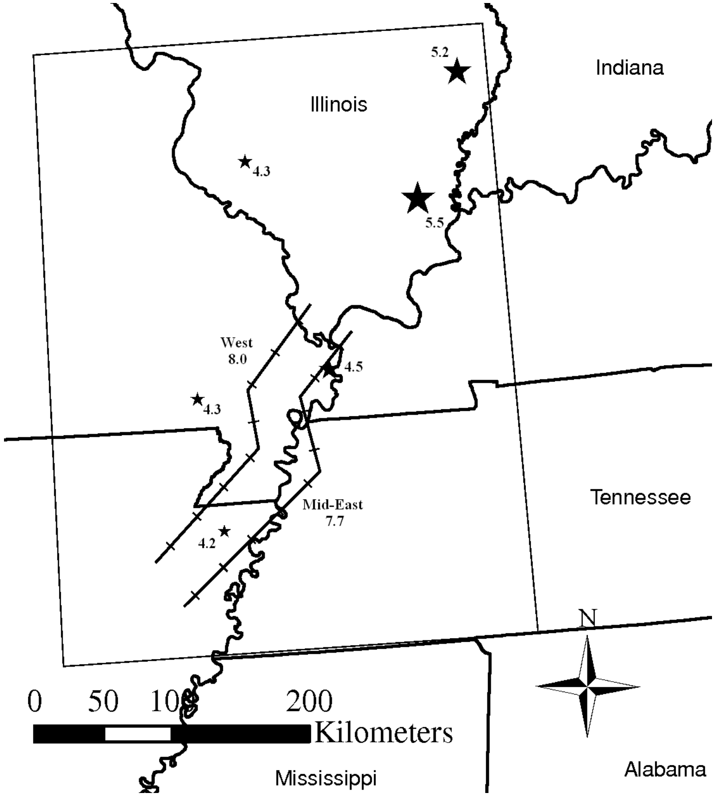
$$\sum_j s_j b_{jkd} - e_{kd} = m_{kd} \quad \forall k, d$$

$$\sum_j \sum_{d,d'} \left(b_{jkd} - \sum_j b_{jkd} s_j \right) \left(b_{jk'd'} - \sum_j b_{jk'd'} s_j \right) s_j + \varsigma_{kk'} = \sigma_{kk'} \quad \forall k \neq k'$$

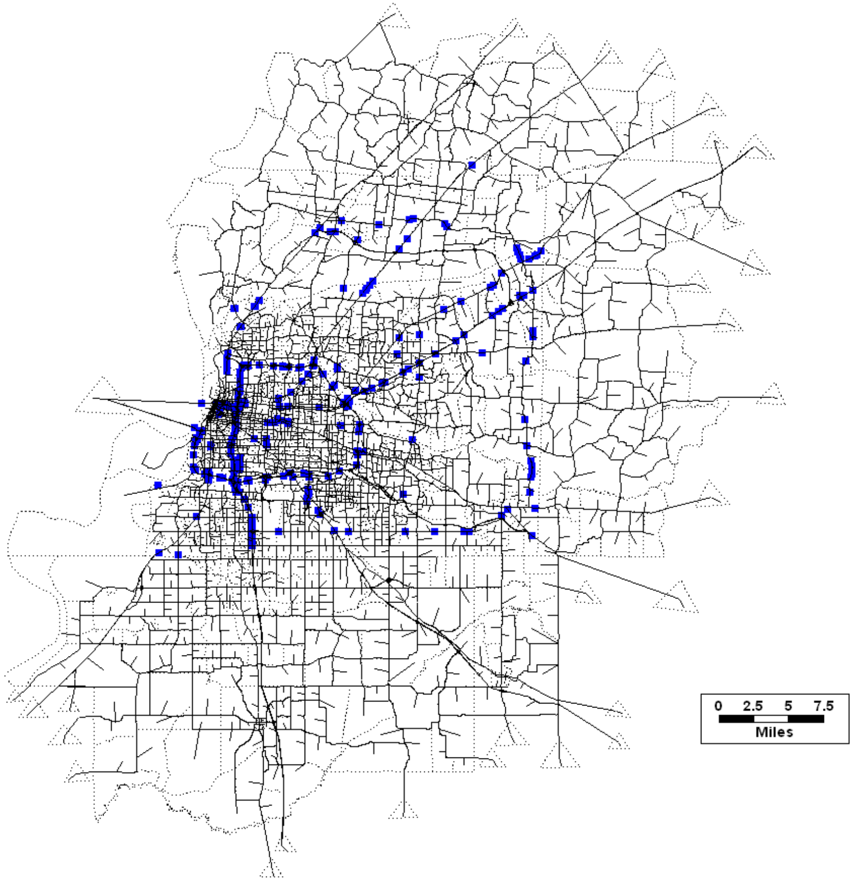
- Iterative procedure to solve
  - Assume all scenarios are equally likely (1/J)
  - Solve the resulting integer nonlinear program for b_{jkd}
  - Assume the values for b_{jkd} and solve nonlinear program for s_j
  - Objective is non-decreasing hence, iterate until no improvement in objective

Results: Memphis Highway Network

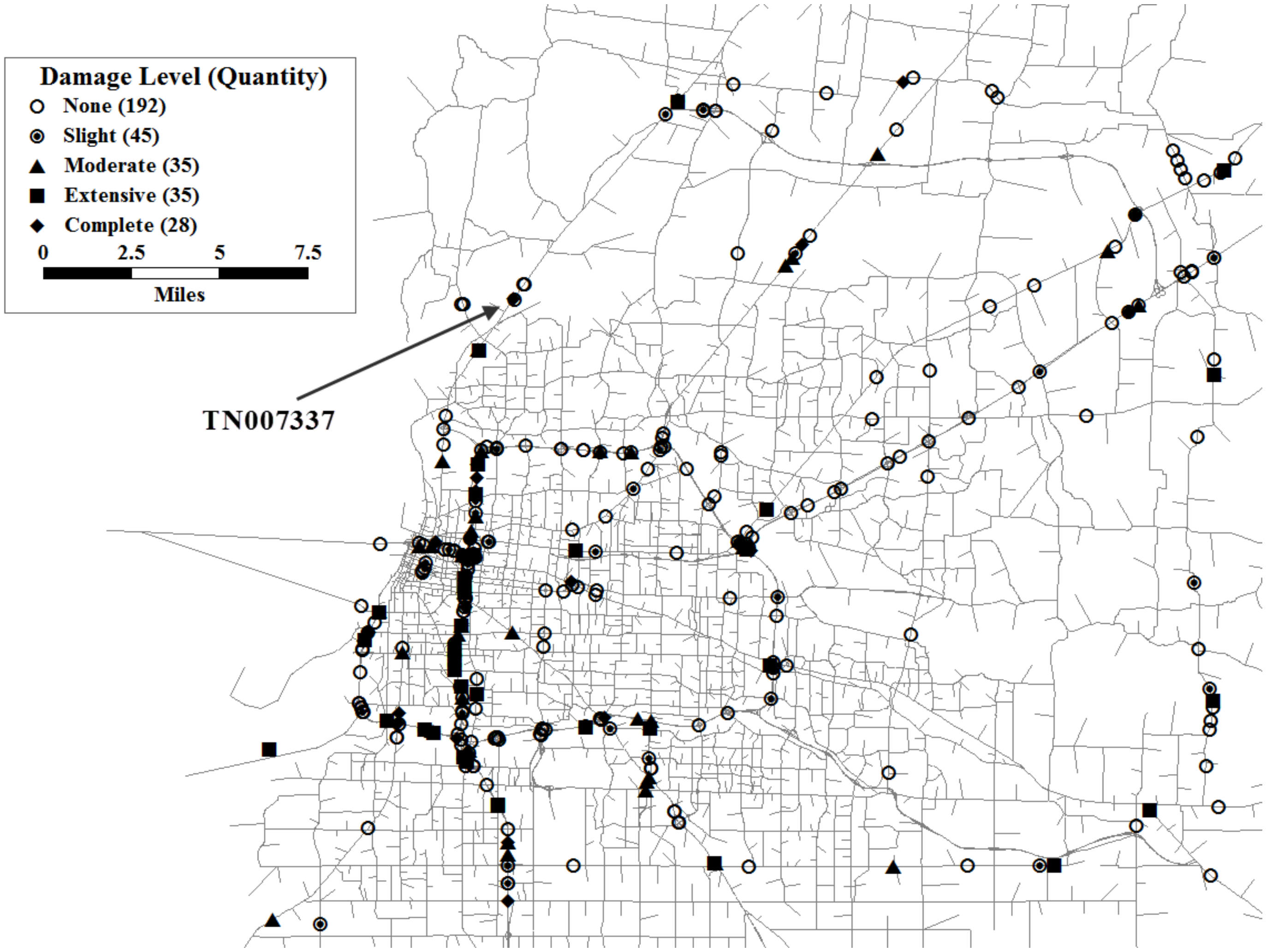
Event: 7.7 moment of magnitude earthquake on the Mississippi River between Kentucky and Mississippi



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



Results: Scenario 1 of 20



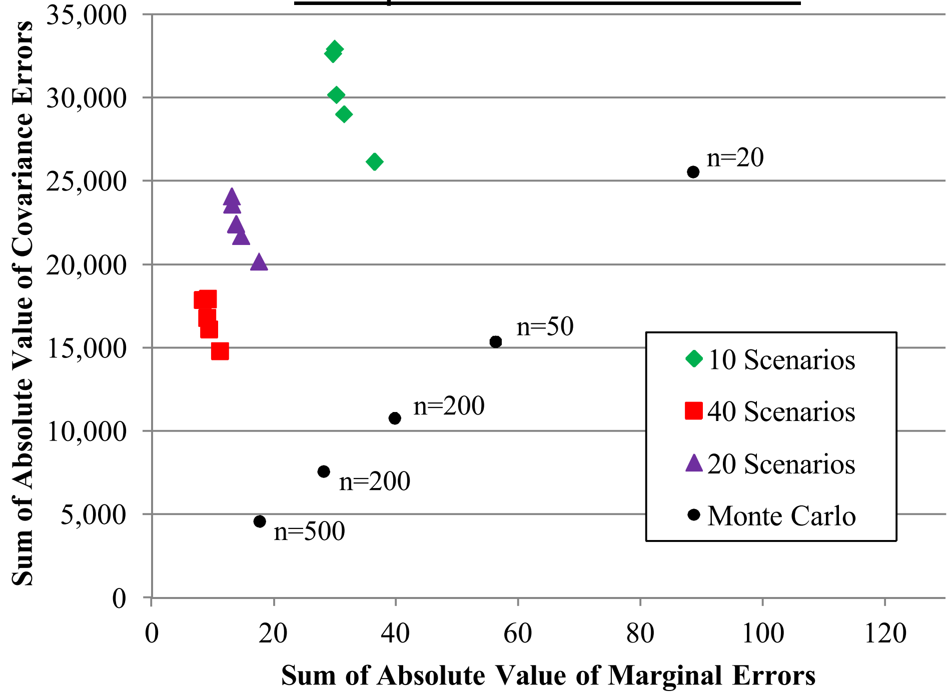
Damage states are then mapped into capacity levels

Results: Errors

Errors for Bridge TN007337 (20 Scenarios)

Damage Level	"True" Vulnerability	Implied Vulnerability	Absolute Error
None	0.105679	0.083762	0.021917
Slight	0.147006	0.151870	0.004864
Moderate	0.149689	0.163832	0.014143
Extensive	0.285269	0.296207	0.010938
Complete	0.312358	0.305121	0.007237

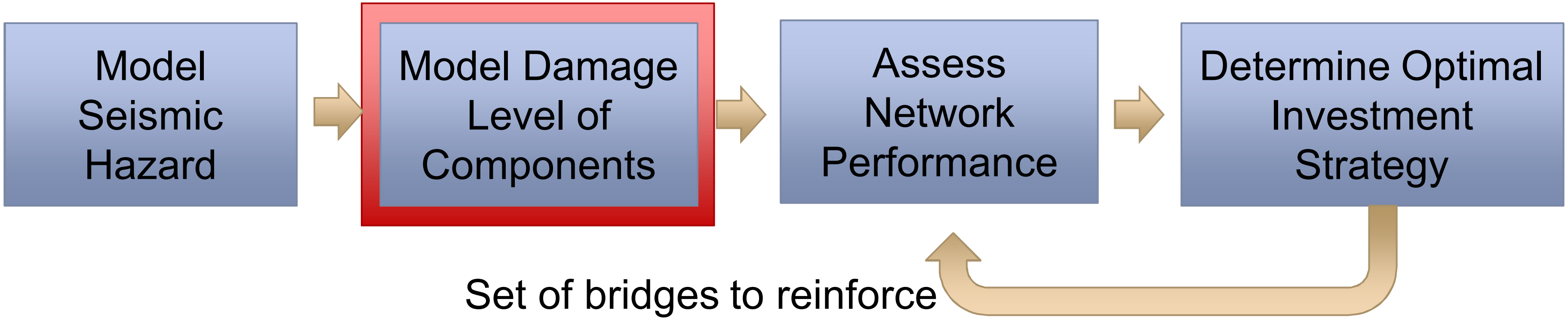
Comparison of Total Errors



Extensions and Future Work

- Consecutive scenario creation
  - Technique extended to capture both mitigated and unmitigated fragility curves
  - Currently consider each event in isolation; could be extended to consider all events
- Considering adding hospital network to model
  - Need to develop fragility curves

Roadmap

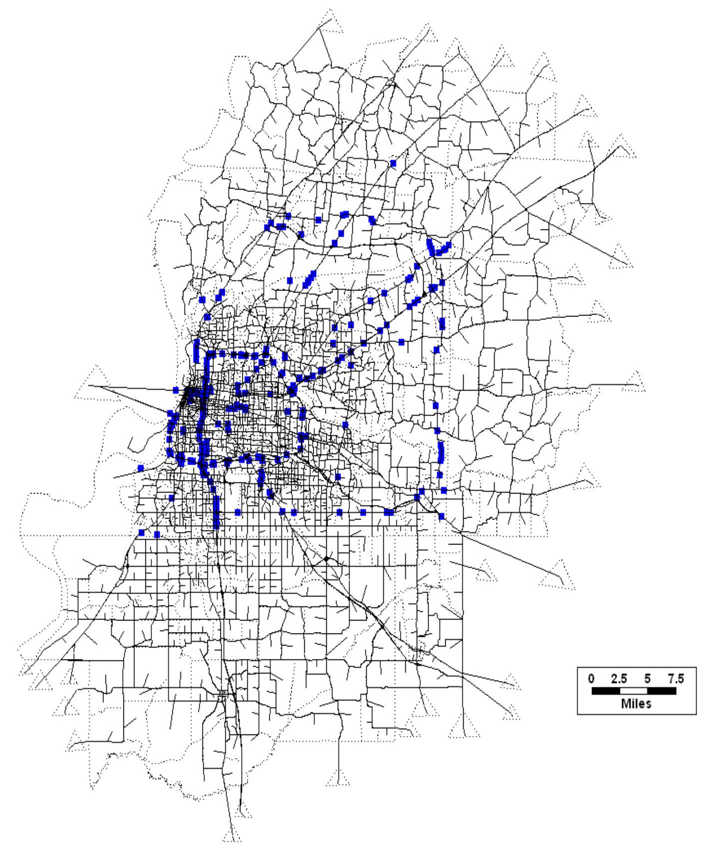


- Previous method allows for representative consequence scenarios to be created
- When consequence scenarios are combined with a network model, performance measures (pre- and post-event) can be calculated

Problem Overview

- Single infrastructure (highway network) overlaid with a pseudo network (hospitals)
- Single threat – earthquakes damaging bridges
- Bridge damage affects both network efficiency (travel time) and connectivity (blocked routes)
- Investments can be made to reinforce bridges to reduce likelihood of damage

Memphis Highway Network

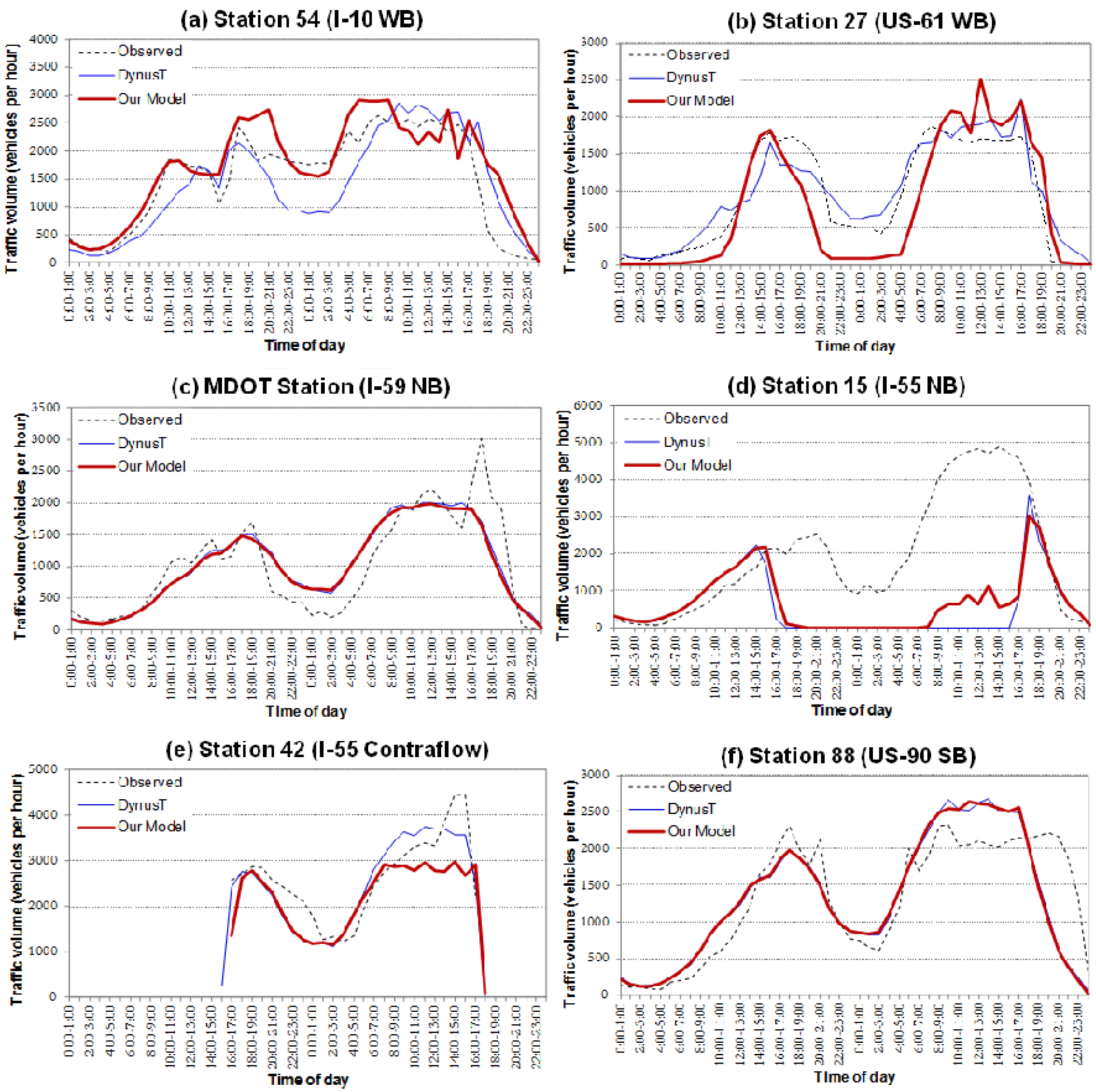


Blue dots represent highway bridges (335 total)

Dynamic Traffic Assignment (DTA)

- Models the movement of a fixed number of vehicles from a collection of origins to a collection of destinations over a well-defined time period
- Comparable to industry standard but much faster
  - Validated against DynusT and link counts during Katrina evacuation
  - For 2 day Katrina evacuation runs in about 10 seconds on 8 cores versus 110 minutes for DynusT
- Li, A., Nozick, L., Davidson, R., Brown, N., Jones, D., and Wolshon, B., "An Approximate Solution Procedure for Dynamic Traffic Assignment", Journal of Transportation Engineering, in press.

Comparison with DynusT, Observations



DTA Algorithm

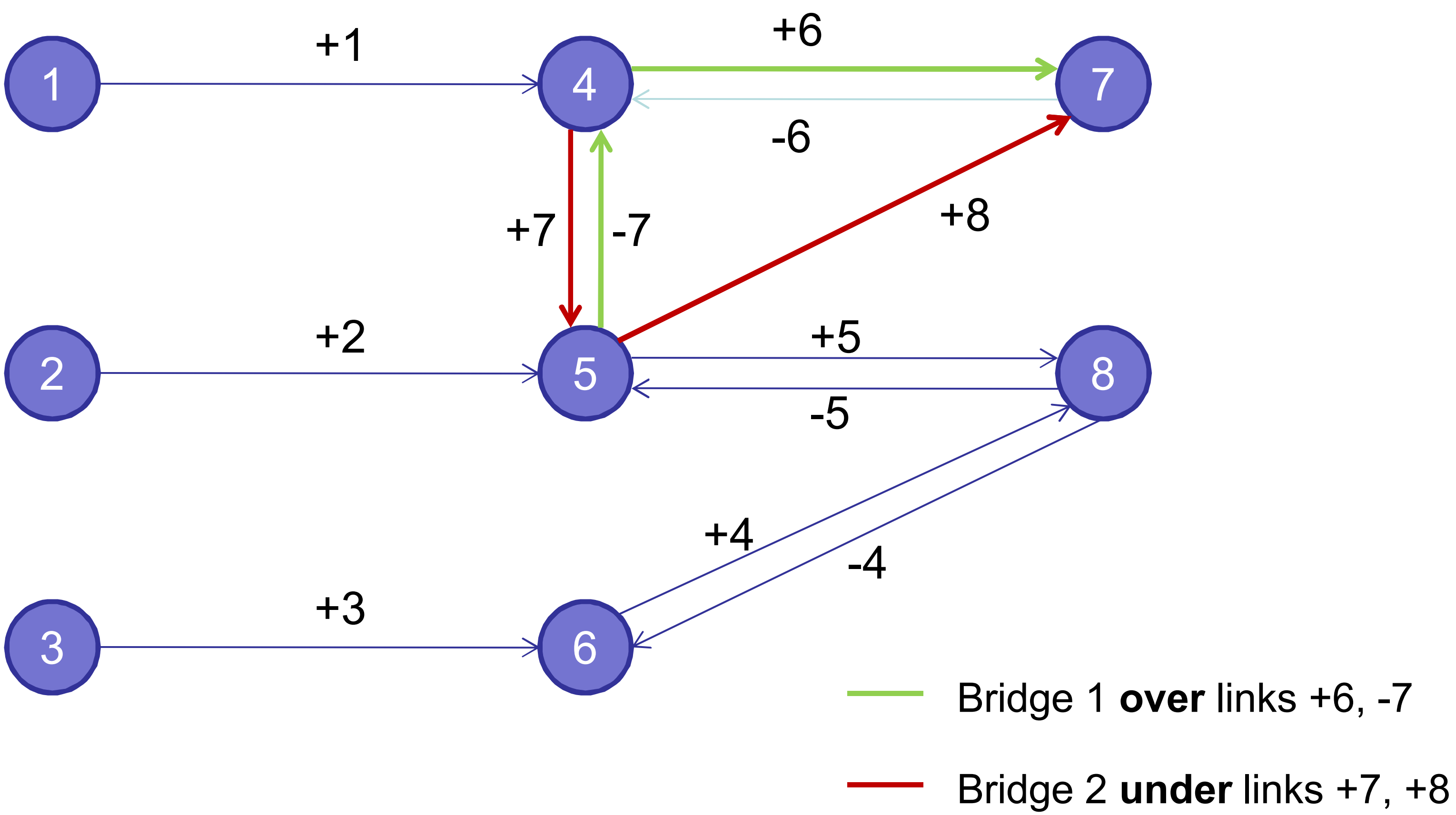
- Incrementally add traffic to the network starting at the beginning of the time horizon.
  - After each time interval when traffic is added, compute travel time on each link during each time period
  - Re-evaluate the shortest path at each time interval using an "all-or-nothing" selection strategy
  - Uses Dijkstra's algorithm for determining the shortest path (travel time) between all OD (origin-destination) pairs
  - Use updated time as basis to add next traffic increment
- Average travel time is determined using the volume-delay function developed by the Bureau of Public Roads (BPR)
  - $T = t_a \left[1 + 0.15 \left(\frac{v_a}{c_a}\right)^4\right]$ (Average Travel Time)
  - t_a = free flow travel time on link *a* per unit time (constant)
  - c_a = capacity of link *a* per unit time (constant)
  - v_a = volume of traffic on link *a* per unit time (variable)

Simple Network Example

Link ID	From node	To node	Direction	Time (min)	Capacity
1	1	4	1	24	20
2	2	5	1	2.4	20
3	3	6	1	4.8	20
4	6	8	1	4.8	40
-4	8	6	-1	4.8	40
5	5	8	1	6	60
-5	8	5	-1	6	60
6	4	7	1	12	100
-6	7	4	-1	12	100
7	4	5	1	24	100
-7	5	4	-1	24	100
8	5	7	1	36	100

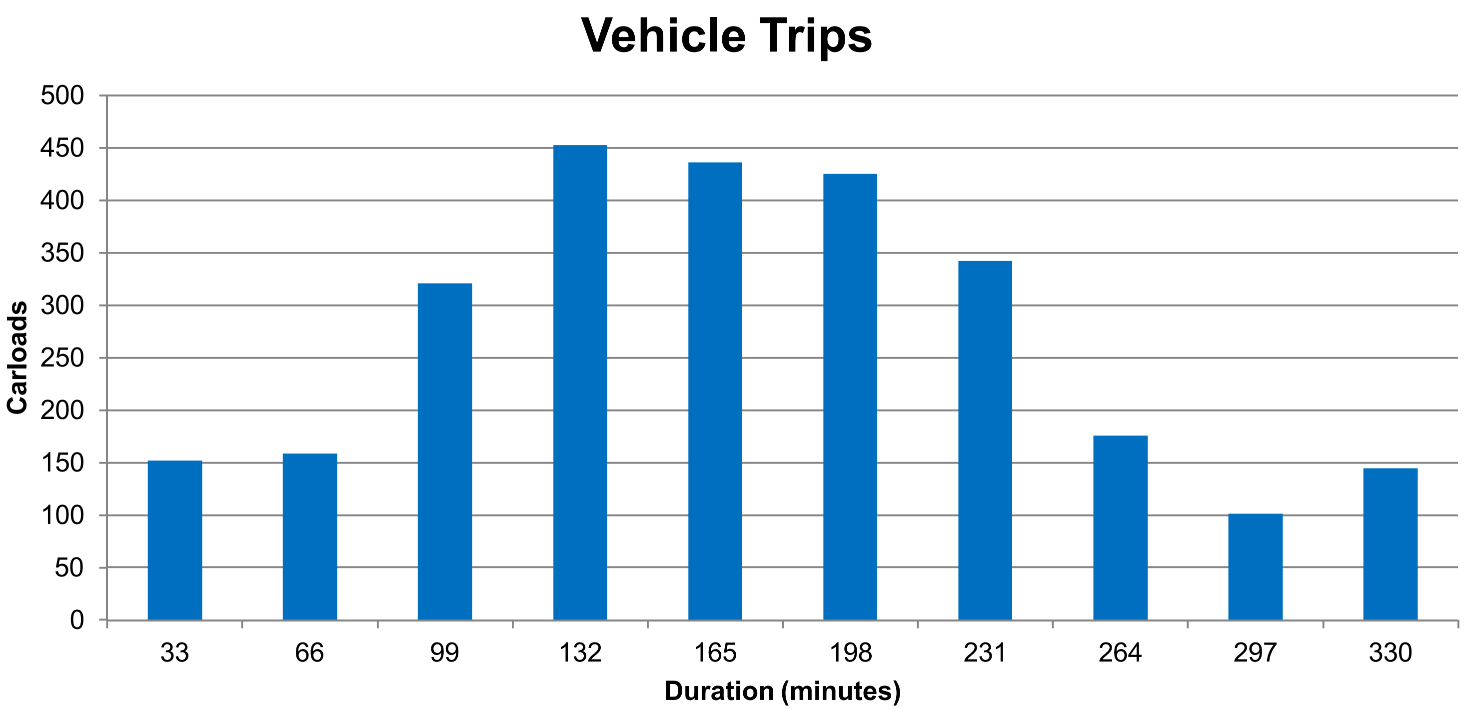
Simple Network Graph

- Network with 8 nodes, 12 links, 6 OD pairs and 2 bridges



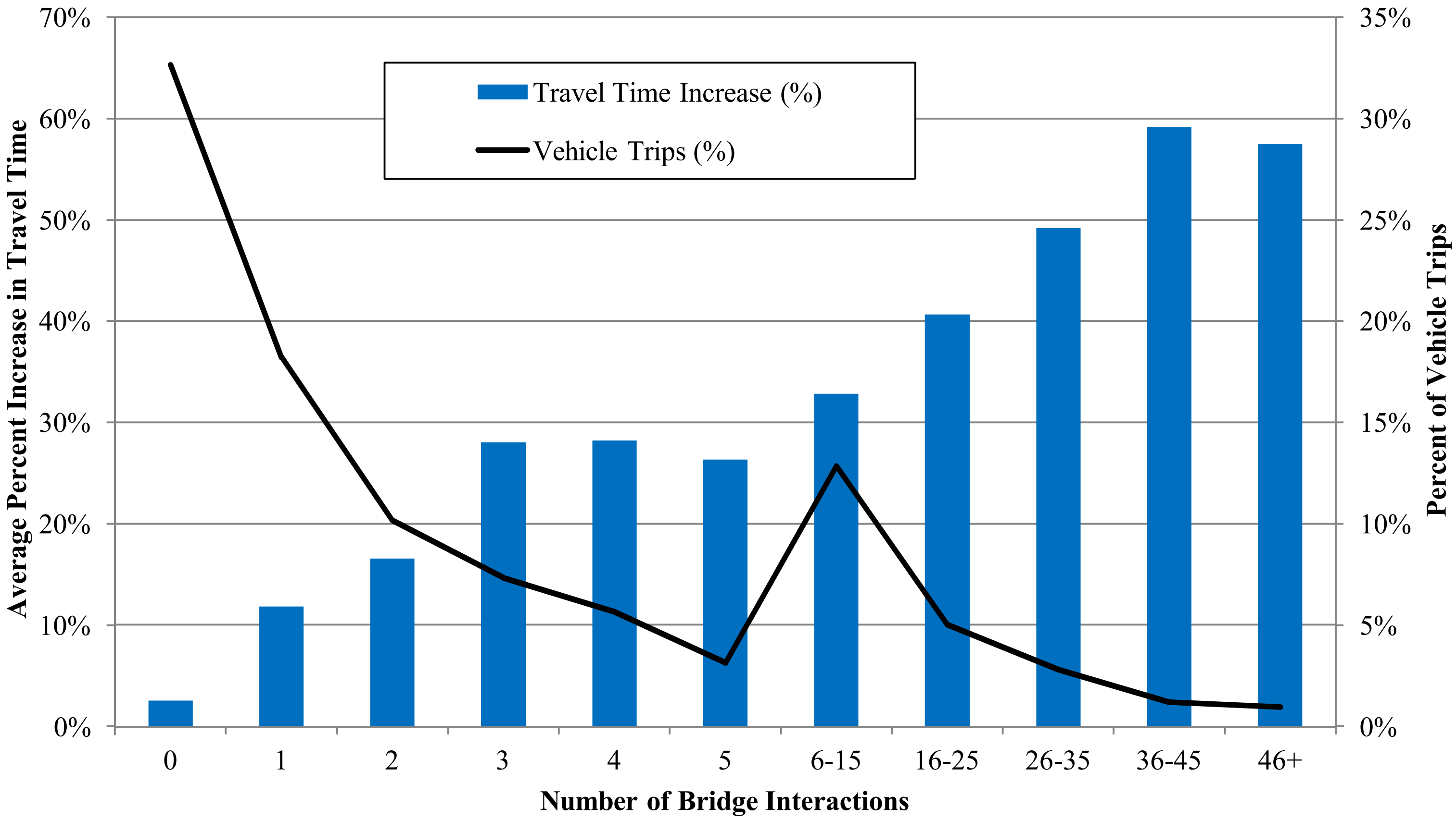
Simple Network Results

- Scenario: Bridge 2 completely destroyed, blocking links +7 and +8, Bridge 1 no damage
- High level results
  - Carloads: 2711 departed, 2645 arrived, 66 stalled (origin 1 has no path to destination 8)
  - Travel times (minutes): min = 8.4, max = 320.9, average = 154.6
- Histogram of travel times

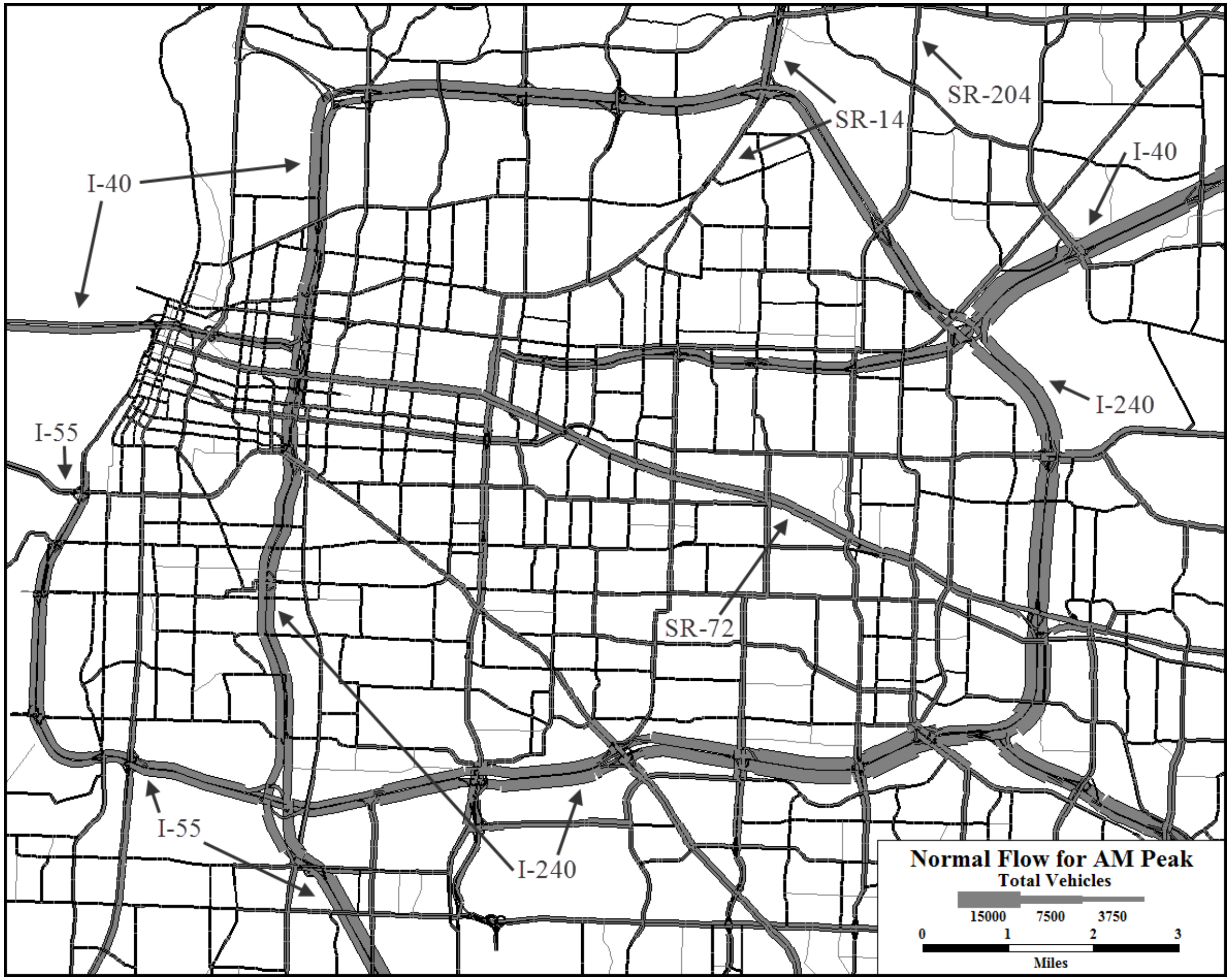


DTA Results

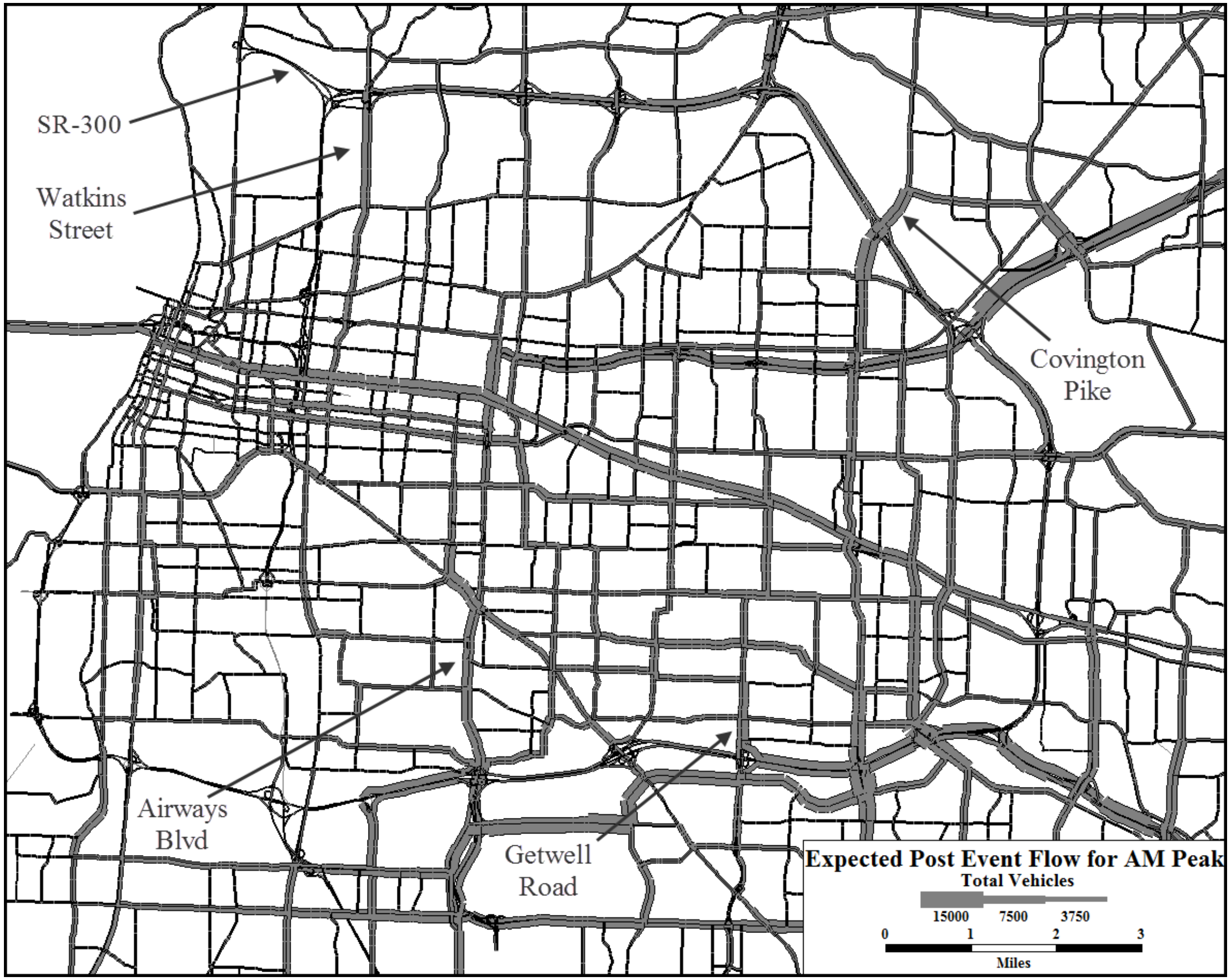
Percent Increase in Travel Time vs. Number of Bridges Crossed



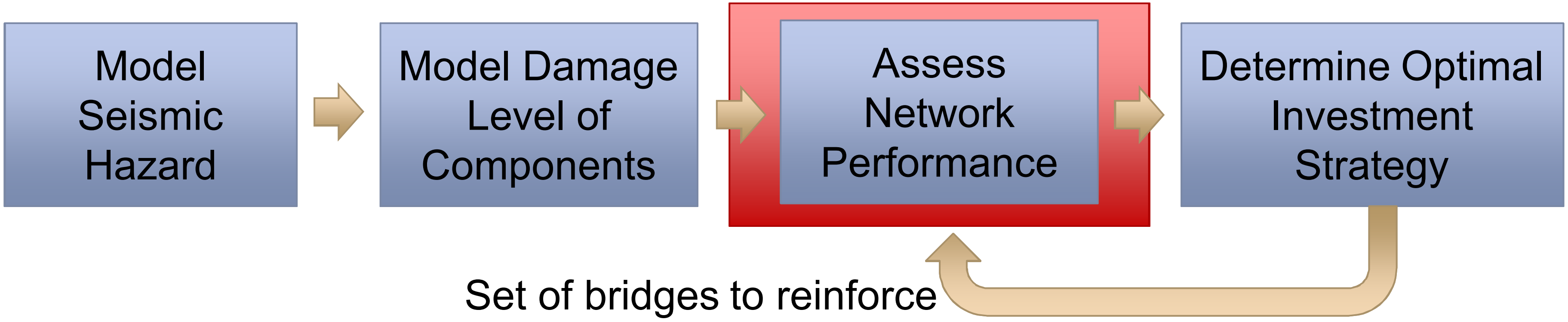
Non-Event AM Volumes



Post Event AM Expected Volumes



Roadmap



- With efficient techniques for assessing network performance, algorithms for determining optimal investment strategies can be developed

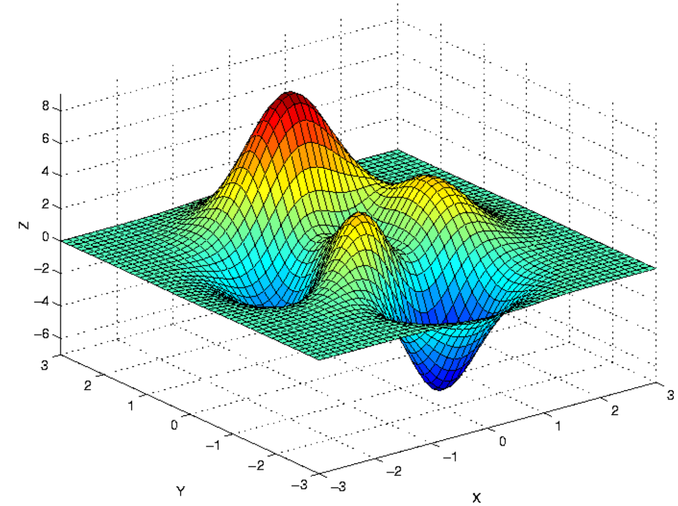
Investment Planning Optimization: Multi-Objective Two Stage Stochastic Program

- Determine optimal investment strategy which:
  - Minimizes travel time across highway network
  - Minimizes travel time from major population centers to nearby hospitals
  - Minimizes investment cost
- Scenarios
  - Two earthquake events
  - Twenty consequence scenarios for each
  - Hazard-consistent probability of occurrence for each

Tabu Search

Sandia National Laboratories

- Heuristic method for finding an optimal solution within a large search space which contains local optima
- Recently selected solutions go on a Tabu List (T) and cannot be re-selected for a fixed number of iterations



- Initial feasible solution, *S* (randomly reinforced bridges), set as global best *G*
- For a finite number of iterations:
  - Generate solutions in local neighborhood, *N* (iteratively swap bridge states)
  - Select best solution *S** in *N*
  - **If** *S** better than *G*
    - *S* == *S** (current solution)
    - G == S* (best global solution)
    - Update *T*
  - **Else** if S* is not on *T*, then *S* == *S** (current solution)
    - Update *T*
  - **Else** continue iterating over *N* until max iterations reached, then reinitialize

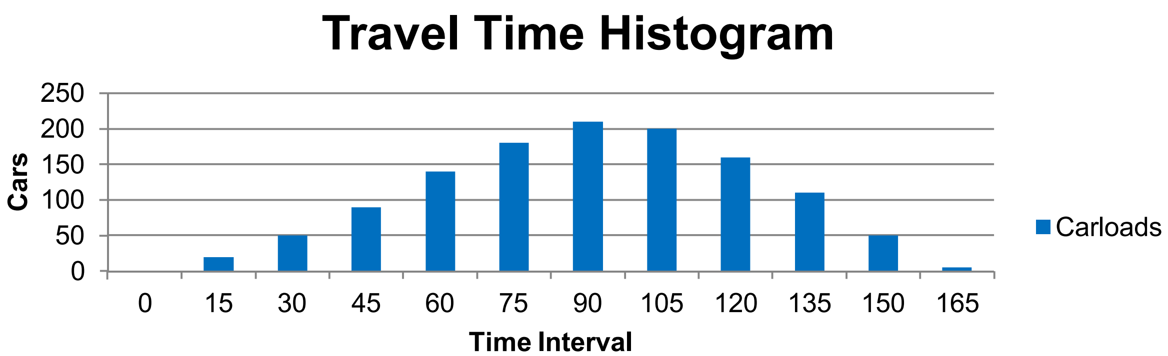
Multi-Objective Optimization

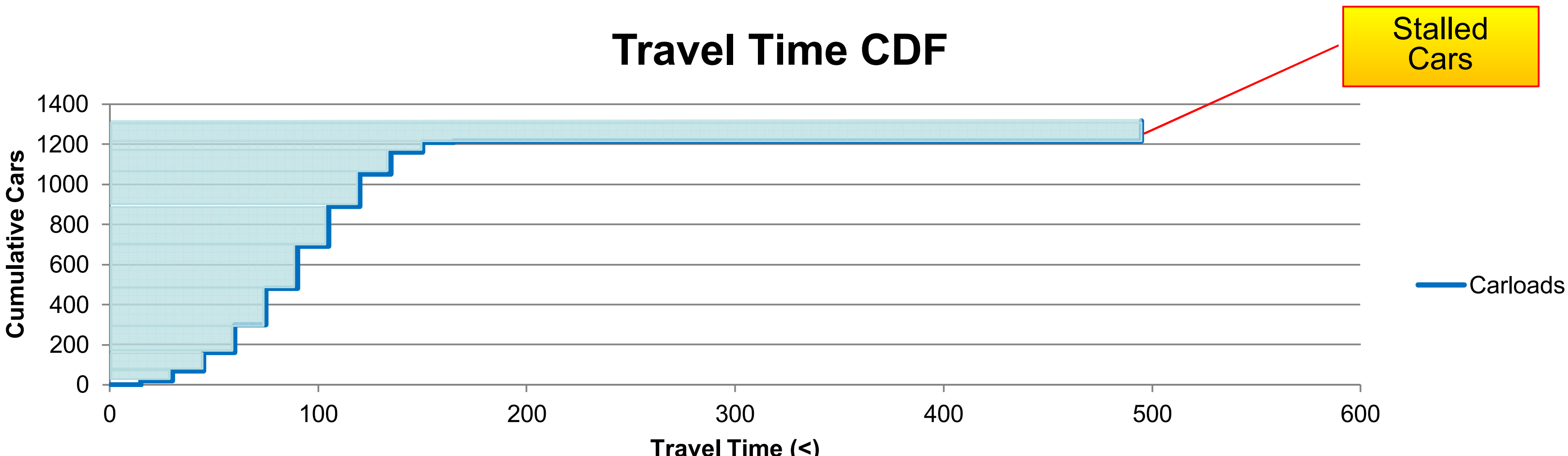
Sandia National Laboratories

- Objective for each scenario is actually a weighted combination of 3 objectives:
  - Travel Time Objective
  - Hospital Connectivity Objective
  - Bridge Mitigation Cost
- The weighting for each objective is determined by:
  - Find the 2 extreme solutions (all/no bridges reinforced)
  - Determine weight for each objective so that they contribute equally
  - Average the weights between the 2 solutions
- Overall objective is a weighted aggregate across 40 earthquake scenarios
  - Each earthquake has 20 scenarios where each scenario has damage states for each bridge with/without reinforcement
  - The objective for a scenario is weighted by the scenario's probability of occurrence

Travel Time Objective

- Find area to "left" of the cumulative histogram curve (CDF)
- Stalled traffic is penalized at 3 times the highest travel time



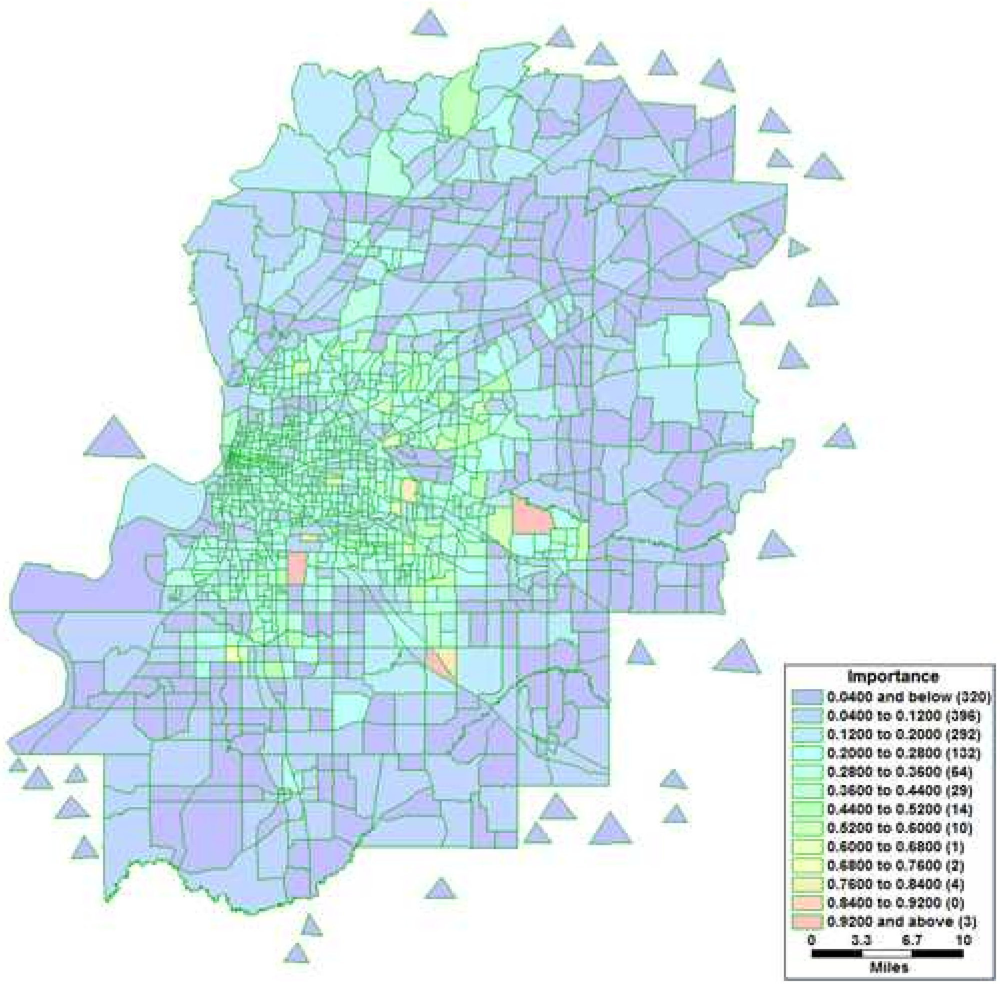


Hospital Connectivity Objective

- Select a set of bridges to reinforce that provides the best possible level of connectivity as determined by:
  - Minimizing the number of people who have no route to any hospital
  - Minimizing the travel time of people who have a route to a hospital
- Memphis network is broken into 1267 traffic analysis zones (TAZs)
  - Each zone contains a centroid where trips originate and terminate
  - Zones with hospitals will be considered destinations
  - All other zones will be considered origins
- Zone importance is based on average number of people in the zone over the course of a day:
  - $\left(\frac{2}{3}\right)\{zone\ population\} + \left(\frac{1}{3}\right)\{zone\ population - employed\ residents + students + employees\}$

Hospital Connectivity Objective (2)

- Map of zone importance in Memphis



Hospital Connectivity Objective (3)

- Objective Calculation across all origins *O* and consequence scenarios *S*

$$min \sum_{s=1}^{S} \sum_{o=1}^{O} p_s w_o f(t_{so})$$

Where:

p_s is the probability of consequence scenario *s*

w_o is the weight or importance associated with origin zone *o*

t_{so} is the 75th percentile of the travel time observations, if connected, else $t_{so} = \infty$

$f(t_{so})$ represents the penalty associated with a hospital connectivity of t_{so}

The penalty term for hospital connectivity is calculated as follow:

$$f(t_{so}) = \begin{cases} p_1 t_{so}, \ b_1 \le t_{so} < b_2 \\ p_i t_{so}, \ b_i \le t_{so} < b_{i+1} \\ p_I t_{so}, \ b_I \le t_{so} \\ M, \ t_{so} = \infty \end{cases}$$

Trip Duration	Penalty
0-8	.1
8-16	1
16-24	2
24-32	4
32-40	7
40+	10
∞	10,000

Implementation

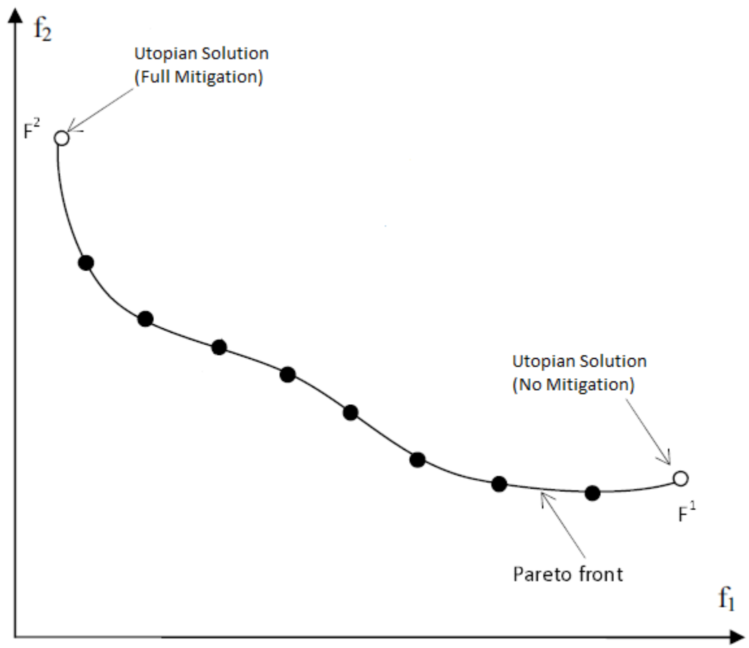
- Speed Optimization
  - Use threading to take advantage of multiple cores
    - Running 8 DTA scenarios in parallel requires 37% of the time compared to sequential processing
  - Combine highway multiple network nodes into "super nodes" (75% reduction)
  - Scenario differencing: only recompute values for those scenarios that change due to a bridge reinforcement
  - For TS neighborhood search, sample top 10 (25%) of earthquake scenarios based on greatest number of bridges impacted
  - Run DTA at 1 hour time intervals
    - Each "full" iteration must reevaluate solution across all scenarios at full time resolution (15 min intervals)
- Cover more of the solution space by executing multiple runs in parallel
  - Spawn multiple instances across a collection of processing nodes
  - Red Sky (SNL supercomputer) used as workhorse
    - 2816 nodes with 8 cores per node = 22,528 cores
    - Each node has dual 2.93 GHz Intel Quad Core processors with 12GB RAM

Parallel Processing

- Master spawns multiple processes using MPI (Message Passing Interface) and communicates via RMI (Remote Method Invocation)
- Each instance starts with a random bridge mitigation strategy
- Best solution from each instance sent back to master which generates a new set of starting points via genetic crossover
  - Solution 1: 1 2 3 4 5 6 7 8 9 10
  - Solution 2: 15 16 17 18 19 20 21 22 23 24
  - Child 1: 1 2 3 15 16 17 18 19 20
  - Child 2: 4 5 6 7 8 9 10 21 22 23 24
- Improvement: generate a correlation matrix for how bridges are related
  - 3 bridges in a row is better to reinforce than only 1 of the bridges

Results

- Generate a collection of the "best" solutions
  - 100 processes over 5 iterations produces 500 solutions of which some will be repeats
  - Use these solutions to generate a Pareto Front of cost-performance trade offs



Improvement: Use ideas from NBI (Normal Boundary Intersection) to provide equally spaced solutions

Conclusions

- Framework for determining optimal infrastructure investments
  - Multiple-hazards
  - Multiple-infrastructures
  - Limited budget
- Draw on a vide variety of techniques and domains
- Focus on computation efficiency
- Vision for the future: provide national and state planners a toolkit for infrastructure investment