Enhancing the resilience of highway networks for extreme events

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Highway networks

- Essential for
  - Quality of life ('hunting and gathering', recreation,…)
  - Commerce and trade
  - Defense
  - Emergency response in event of a disaster
- Comprise systems of roads, bridges, tunnels, slopes, walls…
- One of six essential lifelines: transportation, electric power, water & waste water, gas & liquid fuels, telecommunications, ports & harbors

Vulnerability to extreme events

- Natural events:
  - Flooding and scour (roads, bridges)
  - Ice and debris flow (bridges)
  - Landslide, rock falls, mud slides, (tunnels, roads)
  - Earthquake (bridges, tunnels, slopes, roads…)
  - Wind (bridges)
- Man-made events:
  - Ship collision (bridges)
  - Blast (landslide, structural collapse…)

Presentation background

- In time available, presentation will focus on:
  - *earthquakes* as example of extreme event; applicability to other events is implied
  - highway bridge performance
  - network modeling and performance

Background

- Advances in the state-of-the-art of seismic design for highway bridges can be strongly correlated to the occurrence of damaging earthquakes:
  - 1971 San Fernando
  - 1989 Loma Prieta

Background

- Advances have been numerous and include:
  - Development and acceptance of a *life-safety* philosophy (‘no span shall collapse’)
  - Development and acceptance of ‘capacity’ design
  - Detailing of concrete columns for ductility
  - Retrofitting of inadequate components with restrainers, jackets and wraps, footing overlays…
  - Remediation of liquefiable soils

Background

- Advances continued…
  - Development of earthquake protective systems (response modification devices): seismic isolators, dampers, energy dissipators
  - Preparation of updated specifications (AASHTO, California, South Carolina, …) and retrofit manuals (FHWA)

Background

- But despite these advances, unacceptable damage to bridges and highway systems, continues to occur:
  - 1994 Northridge
  - 1995 Kobe (Japan)
  - 1999 Koaceli (Turkey)
  - 1999 Chi-chi (Taiwan)
  - 2001 Nisqually

Background

Clear message from public that, despite the low loss of life, bridge performance in the Loma Prieta, Northridge and Nisqually earthquakes was unacceptable. Also in Japan, Taiwan and Turkey.

Better performance is required… at little or no additional cost.

The challenge

- During the life of a bridge, earthquakes of varying size will occur from very small to possibly very large events.
- Current design specifications require explicit design for only one earthquake level (e.g. 500 year), and imply that performance will then be acceptable for all other earthquakes, both larger and smaller.

The challenge

- Recent damaging earthquakes suggest that this is not necessarily true, e.g. earthquakes larger than those used in design collapsed bridges in Kobe and Taiwan; and smaller events collapsed spans in CA, eg Loma Prieta
- And in any region where the PGA (peak ground acceleration) increases significantly with return period, this is not likely to be true, such as in central and eastern US (CEUS)

A way forward…

- Performance Based Design (PBD) is intended to *improve the seismic performance of bridges for all earthquakes, both large and small*, by satisfying explicitly stated performance criteria at more than just one earthquake level.
- These criteria vary with earthquake size and bridge importance; e.g. they are more rigorous for structures of greater importance and/or during small (frequent) earthquakes.

Performance-based design

- Performance-based design (PBD)
  - A new development in the design of civil infrastructure for extreme events
  - Life-safety is no longer sole requirement
  - Preserving functionality and minimizing economic loss are additional criteria
  - Performance expectations increase with importance of infrastructure; but may decrease with increasing size or rarity of event
  - Powerful tool for mitigation, pre-event planning and emergency response

Performance-based design

- Three essential steps to the implementation of PBD:
  1. Selection of acceptable performance criteria for each hazard level
  2. Development of bridge technologies to meet these criteria
  3. Development of analysis and design methodologies to verify that criteria will be satisfied

Performance-based design

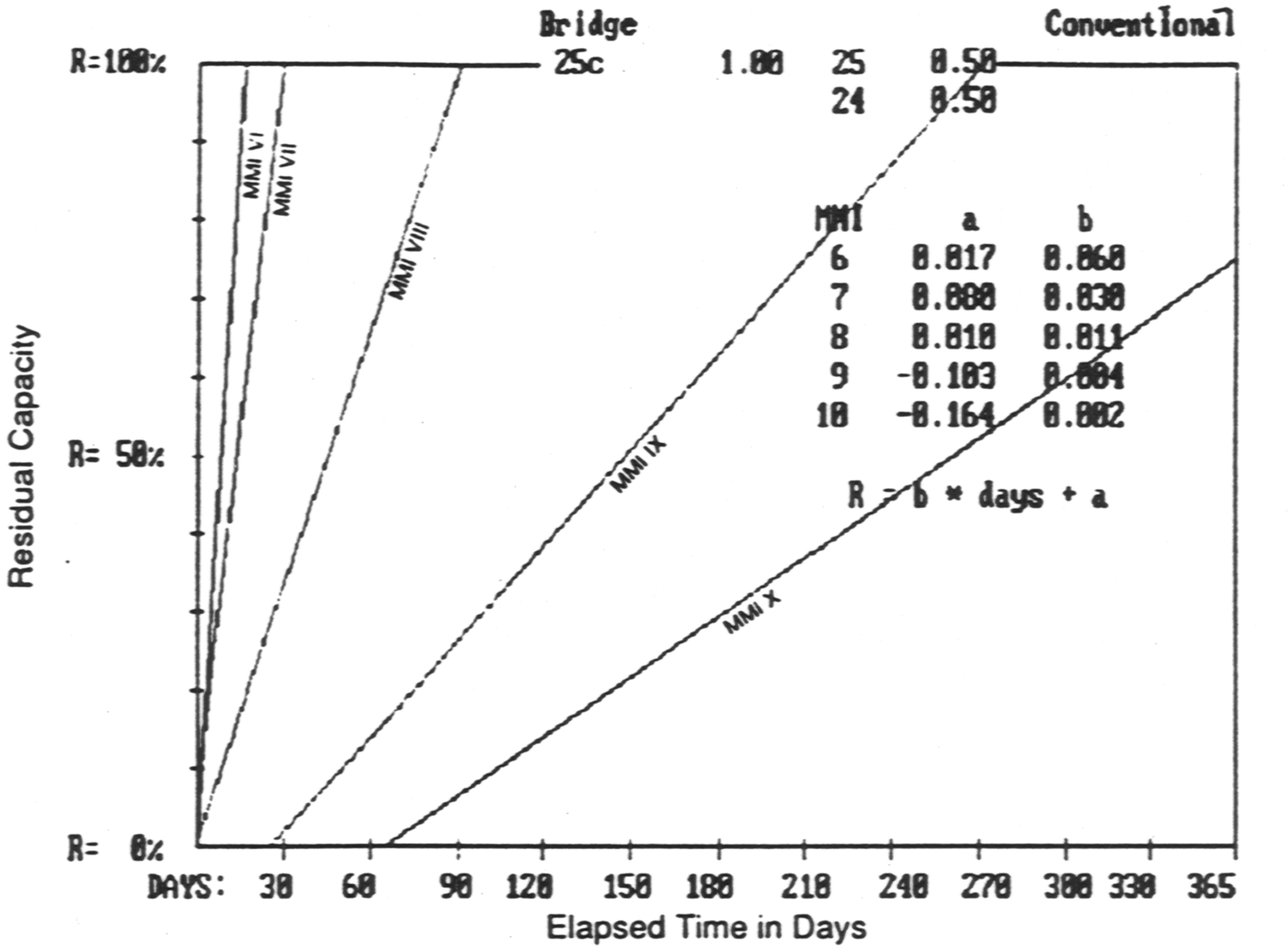
- PBD requires that we know:
  - seismic hazard (seismological challenge)
  - geotechnical hazard (geotechnical / structural challenge)
  - structural damage states (structural /geotechnical challenge)
  - relationship between damage and functionality (multi-disciplinary challenge)

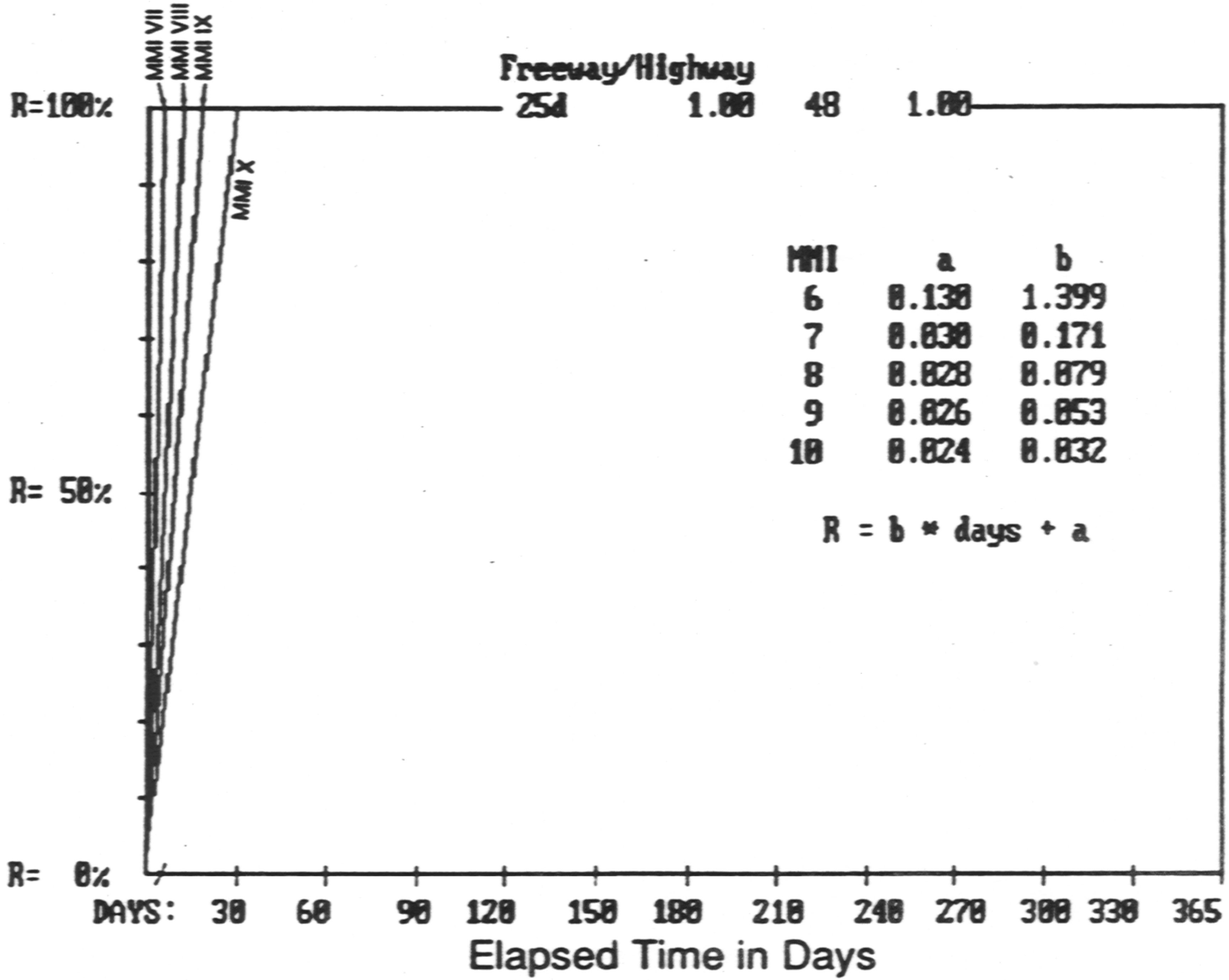
Performance-based design

- Despite uncertainties, specifications and design guides using performance-based design (PBD) principles, have been developed in United States (and elsewhere) for
  - seismic design of new bridges, and
  - seismic retrofit of existing bridges
- But PBD of bridges alone is insufficient to
  - meet societal expectations of system performance (i.e. network functionality), and
  - reduce cost implications of upgrading every bridge in existing inventory

Network functionality

- Component vs system performance
- Highway systems are complex distributed networks with performance attributes that far exceed the sum of their component parts
- Similar to electric power,
  water and wastewater,
  gas and liquid fuels, and
  telecommunication systems


Bridge
Conventional
R=100%
25c
1.00
25
0.50
24
0.50
MMI VI
MMI VII
MMI VIII
MMI IX
MMI X
MMI
a
b
6
0.017
0.060
7
0.000
0.030
8
0.010
0.011
9
-0.103
0.004
10
-0.164
0.002
R = b * days + a
Residual Capacity
R= 50%
R= 0%
DAYS:
30
60
90
120
150
180
210
240
270
300
330
365
Elapsed Time in Days



MMI VII
MMI VIII
MMI IX
MMI X
Freeway/Highway
R=100%
25d 1.00 48 1.00
R= 50%
R= 0%
MMI a b
6 0.130 1.399
7 0.030 0.171
8 0.028 0.079
9 0.026 0.053
10 0.024 0.032
R = b * days + a
DAYS: 30 60 90 120 150 180 210 240 270 300 330 365
Elapsed Time in Days

Observation

- PBD for bridges is not sufficient. May overestimate vulnerability of system and not necessarily be best use of scarce resources.

- PBD of transportation network is required

Performance-based design of *highway networks*

1. Determine acceptable performance criteria for *network* for each hazard level

2. Design and verify *network* against selected performance criteria

1a. Hazard level and system damage states

- Hazard level:
  - Earthquake characterization: spectral ordinates, peak ground acceleration and peak ground displacement
  - Return period: frequent (150 year), expected (500 year), rare (2500 year)
  - Geotechnical hazards: soil amplification, liquefaction, landslide,

1b. Hazard level and system damage states

- Damage states
  - Bridge damage: component failure, partial or complete collapse
  - Pavement failure
  - Slope and embankment failures
  - Retaining wall and tunnel damage
  - Signage damage
  - Control system failures (electric power and communication failures)

1c. Performance criteria

- Possible criteria for highway systems include:
  - Total vehicle *hours* traveled post and pre-earthquake (congestion)
  - Total vehicle *miles* traveled post and pre-earthquake (detour length)
  - Time delay between critical origin/destination pairs (e.g. from damaged regions to emergency hospitals)
  - Restoration time (in days) to restore system to say 80% of pre-earthquake capacity

1d. Example: Performance criteria matrix

Earthquake Level	**System A** (e.g. standard)	**System B** (e.g. essential)
Expected (500 year)	$T_{80} < 2$ $T_{100} < 7$	$T_{80} < 1$ $T_{100} < 1$
Rare (2500 year)	$T_{80} < 30$ $T_{100} < 90$	$T_{80} < 7$ $T_{100} < 30$

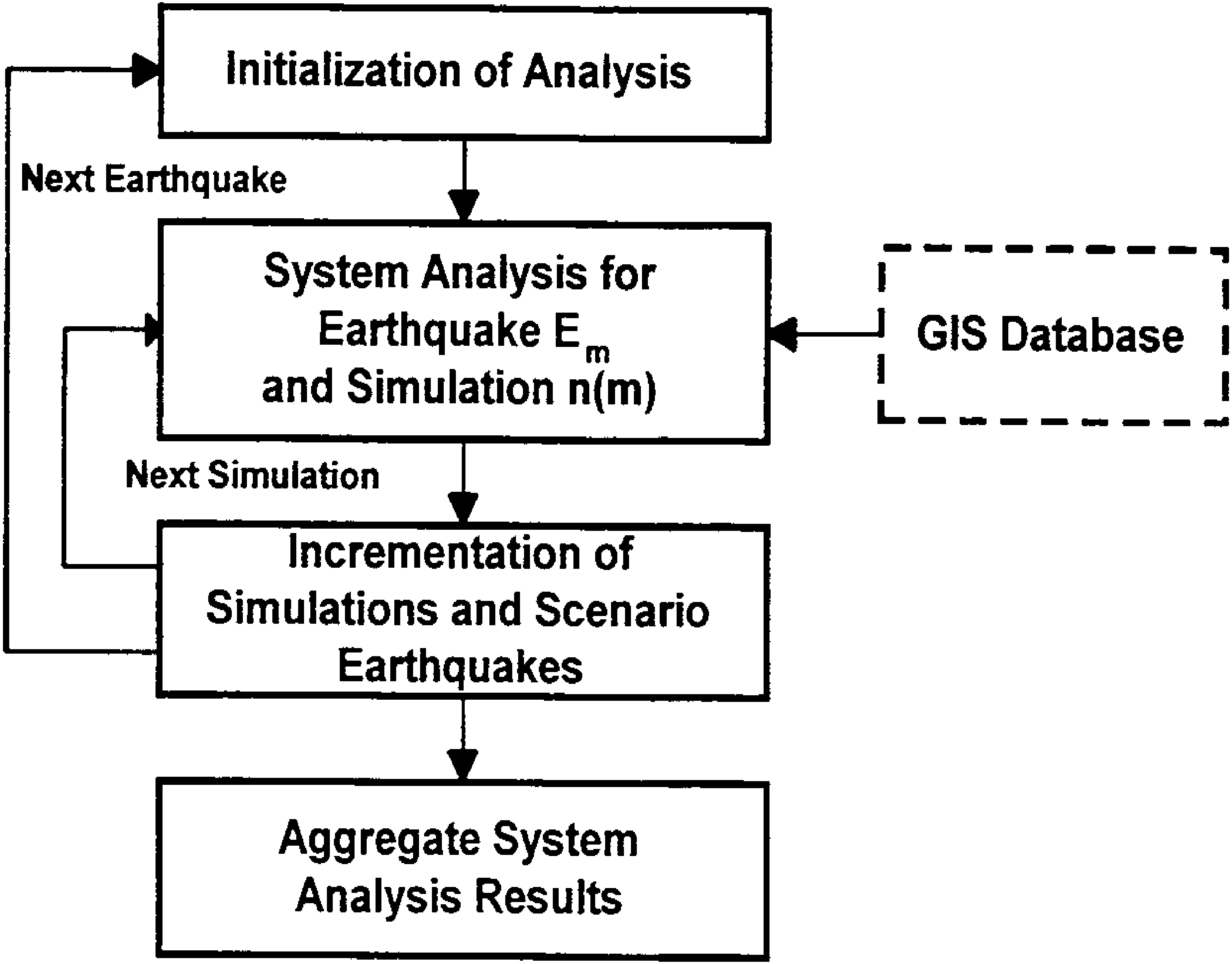
T_{80} and T_{100} are restoration times (days) to 80% and 100% capacity

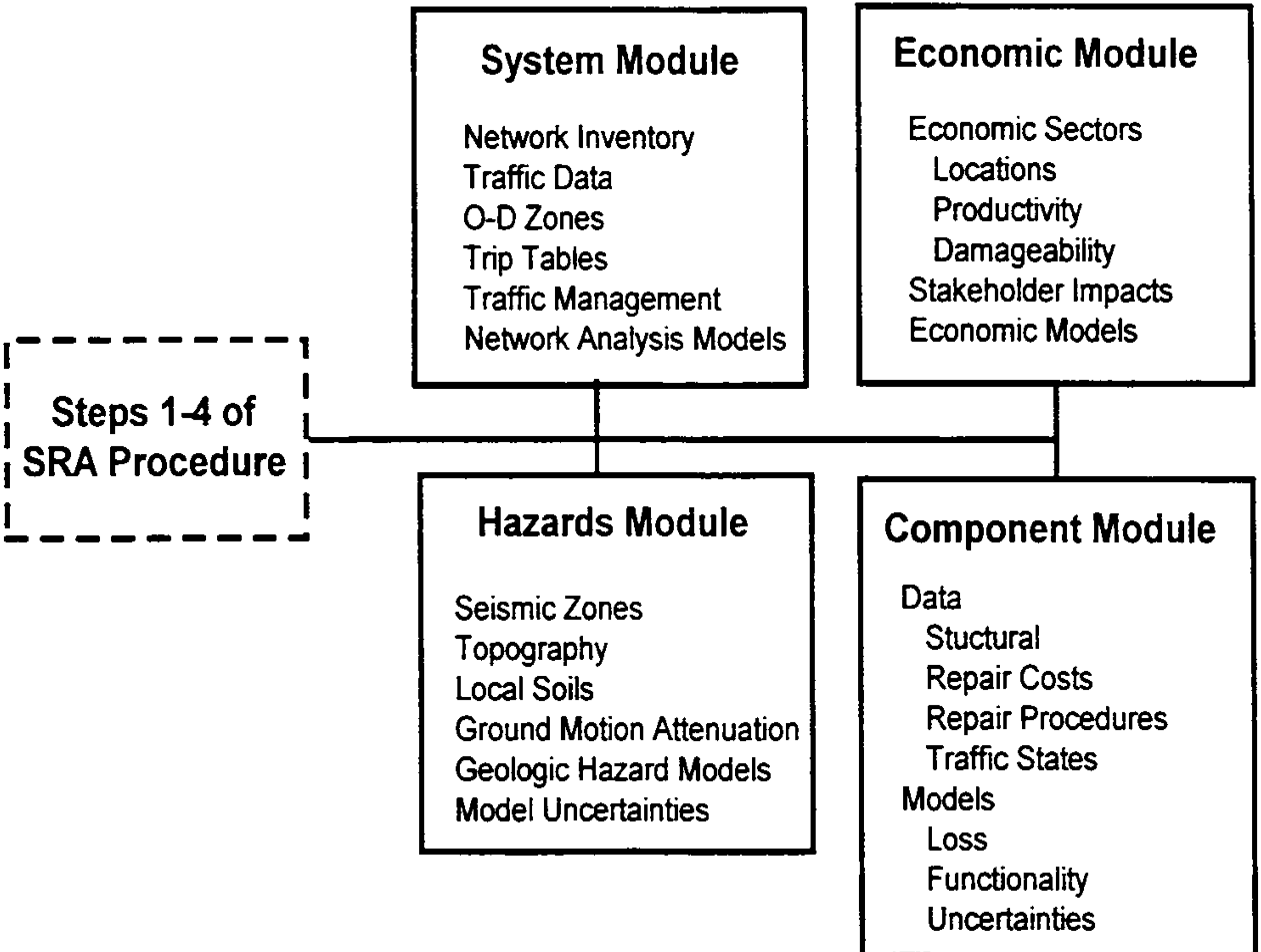
2a. Design and verification

- Verify system satisfies performance and retrofit accordingly:
  a. Calculate damage states for each hazard level (e.g. bridge component failures).
  b. Estimate system performance for the calculated damage states (e.g. time to reach 80% capacity).
  c. If performance is unacceptable, retrofit the system (e.g. strengthen one or more bridges) and reanalyze. Repeat until performance is acceptable.

2b. Design and verification

- Seismic Risk Assessment (SRA) methods may be used to estimate direct and indirect losses for highway systems, in a probabilistic format
- Werner et al, ***Seismic Risk Analysis of Highway Systems***, Technical Report MCEER 00-0014, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, Buffalo, NY, 2000


Initialization of Analysis
Next Earthquake
System Analysis for Earthquake E_m and Simulation n(m)
GIS Database
Next Simulation
Incrementation of Simulations and Scenario Earthquakes
Aggregate System Analysis Results


System Module
Network Inventory
Traffic Data
O-D Zones
Trip Tables
Traffic Management
Network Analysis Models
Economic Module
Economic Sectors
Locations
Productivity
Damageability
Stakeholder Impacts
Economic Models
Steps 1-4 of
SRA Procedure
Hazards Module
Seismic Zones
Topography
Local Soils
Ground Motion Attenuation
Geologic Hazard Models
Model Uncertainties
Component Module
Data
Stuctural
Repair Costs
Repair Procedures
Traffic States
Models
Loss
Functionality
Uncertainties

2c. Design and verification

- GIS-based for data management and display.
- Modularity, for updating database, based on experience, research and development and testing sensitivity.
- Risk-based, to include uncertainties in earthquake ground motions, and structure modeling in a rational manner

2d. Design and verification SRA example: Memphis, TN

- City of Memphis, Shelby County, TN
  - Close to New Madrid seismic zone
  - Three Interstates: I-40, I-55 and I-240
  - Two crossings of the Mississippi (I-40 and I-55)
  - Major transportation center(s)
  - 286 bridges


Memphis
Gen. DeWitt Spain Downtown Airport
Frayser Blvd.
Lake Windermere
Raleigh Springs Mall
Yale Rd.
Sky Lake
Range Line Rd.
Allen Rd.
James Rd.
Raleigh
Stage Rd.
Bartlett
Whitney Av.
New Allen
LOOSAHATCHIE BAR
Memphis
J.F.K. Park
Covington Pike
Lagrange
Wolf
Harrington
Sycamore View
Douglas Park
Memphis Nat'l. Cem.
St. Jude Childrens Research Hosp.
MUD I.
Thomas St.
Watkins St.
McLean Av.
Chelsea Av.
Hollywood St.
Warford St.
Jackson Av.
Pleasant View Rd.
Macon Rd.
ARKANSAS
Cypress
The Pyramid
Rhodes Coll.
North Pkwy.
Summer Av.
Stratford Rd.
Harrison
National St.
Cleveland St.
Zoo
Mus. of Art
Overton Park
Broad St.
SAM COOPER BLVD.
Highland St.
Graham St.
Mendenhall Rd.
Tennessee Welcome Cen. & Memphis Vis. Cen.
C. of C.
C.H.
Conv. Cen.
Univ. of Tenn. Health Sci. Cen.
Poplar Av.
Conv. & Vis. Bur.
Nat'l. Civil Rights Mus.
V.A. Med. Cen.
Meth. Hosp.
Union Av.
Southern Coll. of Optometry
E. Parkway
Pink Palace Mus.
Walnut Grove Rd.
Galloway Park
White Station Rd.
Shelby Farms
Christian Bros. Univ.
Oak Court Mall
Mississippi
Crump Blvd.
Miss. Blvd.
Bellevue Blvd.
Central Av.
Liberty Bowl Stad.
Frgrds.
Southern Av.
Poplar Av.
Children's Mus.
Univ. of Memphis
Goodlett St.
Audubon Pk.
Botanical Gardens
Lemoyne-Owen Coll.
Mid-South Coliseum
S. Parkway East
South Parkway
Park Av.
Rhodes Av.
Harding Univ. Grad. School of Religion
Martin Luther King Park
Lamar Av.
Kimball Rd.
Pine Hills Park
McKellar Lake
Florida St.
3rd St.
Airways Blvd.
Prescott Rd.
Getwell Rd.
Quince Rd.
Mt. Moriah Rd.
Mallory Av.
The Mall of Memphis
Ball Rd.
Mt. Moriah Rd.
Johns Canal
Creek Drainage
American Way
West Junction
T.O. Fuller State Park
Nonconnah Rd.
Brooks Rd.
Nonconnah
Democrat Rd.
Fox Meadows
Knight Arnold Rd.
Memphis Int'l. Arpt.
Eastwood Med. Cen.
Perkins Rd.
Hickory Ridge Mall
Mitchell Rd.
Winchester Rd.
Weaver Rd.
Chucalissa Archaeological Museum
Graceland
Neely Rd.
Elvis Presley Blvd.
Mill
Airways Rd.
T.I.C.
Winchester Rd.
Hurricane
Tchulahoma Rd.
Raines Rd.
Swinnea Rd.
Branch Rd.
Hickory Hill Rd.
0 1 2 3 Mi.
0 1 2 3 4 Km.
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1
2
3

2d. SRA example continued

- Scenario earthquake: M=5.5 at an average epicentral distance of 43 km
- Bridge vulnerability functions based on ATC 25
- Traffic flow data provided by Memphis and Shelby County OPD
- O-D times estimated using MINUTP for pre- and post-earthquake conditions

2d. SRA example continued: Overall system performance

	Pre-earth-quake value	Value @ T=3 days	Increase over pre-earth-quake value	Value @ T=6 months	Increase over pre-earth-quake value
Total vehicle time (10^5 hrs) traveled in 24-hour period	3.73	4.99	33.8%	4.46	19.6%
Total travel distance in 24-hour period (10^6 miles)	15.5	15.6	small	15.6	small

2d. SRA example continued: Overall system performance

	Pre-earth-quake value	Value @ T=3 days	Change from pre-earth-quake value	Value @ T=6 months	Change from pre-earth-quake value
System speed (= travel distance / vehicle hours, mph)	41.6	31.3	-24.7%	35.0	-15.9%
System capacity (% of pre-earthquake value)		75%		84%	

Conclusions

- Societal demand for resilient lifeline networks (at no additional cost) is a major challenge for research community
- *Performance-based design* is an attractive way to frame the problem and articulate a solution

Conclusions

- Research needs are
  - Ground motions (500, 1000, ... 2500 year spectral ordinates, spatial variation, near fault motions)
  - Geotechnical (liquefaction, spreading effects on foundations, soil amplification...)
  - Structural (soil-structure interaction, bridge damage states, smarter bridges, new materials...)

Conclusions

- Performance-based design for highway networks…
  - Is feasible provided
    - a suite of credible fragility functions for all highway system components (bridges, tunnels, slopes walls…) can be developed, and
    - sophisticated traffic flow modeling procedures can be developed
  - Will be a powerful tool for mitigation, pre-event planning and emergency response

Acknowledgements

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