Bridge Failure Consequences

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Influencing factors

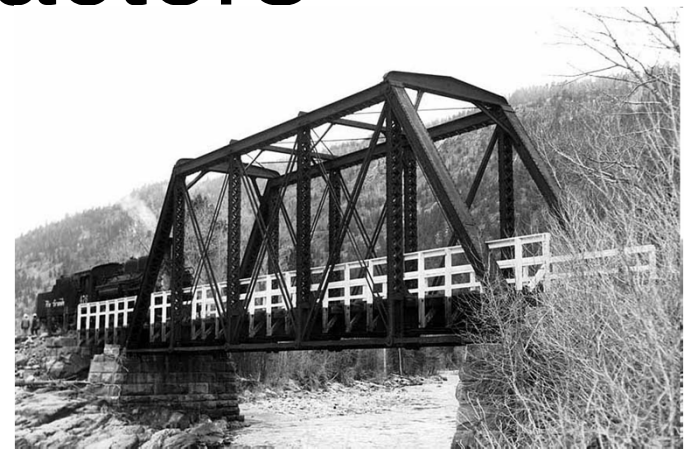
- Source and nature of hazard (*magnitude & duration*)
- Bridge type (*structural form, material used, age, condition, quality of construction*) *VULNERABILITY*
- Bridge location (*type of road or rail route, traffic intensity, rural vs. urban, availability of emergency services, labour & material transportation*)
- Time of failure (*day vs. night, peak vs. off-peak*)

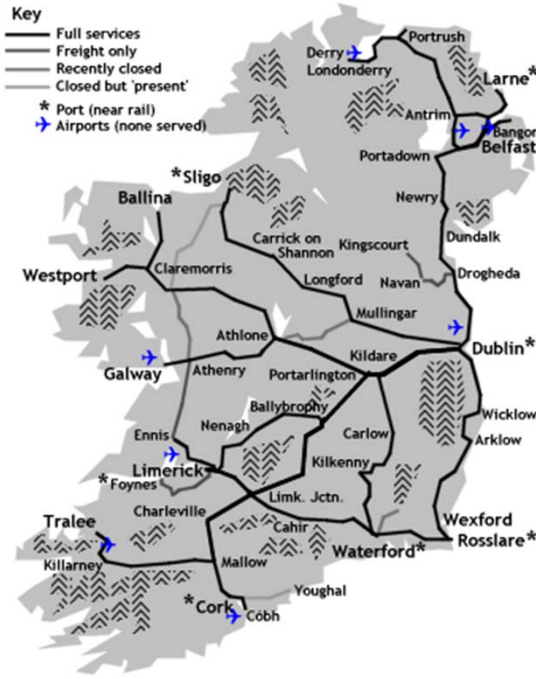
Influencing factors

- Consequence modelling depends on:
  - System boundaries
  - Time frame considered
- System boundaries
  - Structural domain
  - Spatial domain
- Time frame
  - Short term post-event
  - Longer term, equilibria

Influencing factors

- System boundaries
  - Structural domain (structural system itself)
  - Spatial domain (transportation network)
- Extent of spatial domain
  - Single route with diversions
  - Wider network (redundancy)
- Further layers can be added (environment, society, …)





Eurocode treatment of consequences

CC3	**High** consequence for loss of human life, *and* economic, social or environmental consequences **very great**
CC2	**Medium** consequence for loss of human life, *and* economic, social or environmental consequences **considerable**
CC1	**Low** consequence for loss of human life, *and* economic, social or environmental consequences **small or negligible**

- Eurocode lacks classification for bridge structures
- In practice, majority of bridges designed as CC2 or CC3
- All major bridges designed as CC3

Classification of consequences

Consequence categories	Examples
Human	Fatalities Injuries
Economic	Replacement / reconstruction cost Repair costs Loss of functionality/downtime Traffic delay / re-routing costs Traffic management costs Clean up costs Rescue costs Regional economic effect Loss of business Investigations / compensations
Environmental	CO_2 Emissions Energy use Pollutant releases
Societal	Loss of reputation / public confidence Changes in professional practice Loss of business

Often practical to express all consequences in terms of monetary units

Human consequences

- ***Fatalities*** and / or ***injuries***
- Highly variable in terms of predicting & valuing
- Valuation of human life

  - UK DfT: £1.43 million for road fatalities (2005 prices)
  - EU: €1.5 million for road fatalities
  - RSSB: £3.46 million for rail fatalities (2003 prices)
  - HSE: £1 million for fatality (2001 prices)

- Encompass direct human and economic loss i.e. loss of output, medical costs, amount to reflect pain & grief

Human consequences

- Estimation of number of casualties / injuries
- Regional loss estimation framework HAZUS
- Number of people on or under bridges:

$$NBRDG = CDF \times Commuter\ Population$$

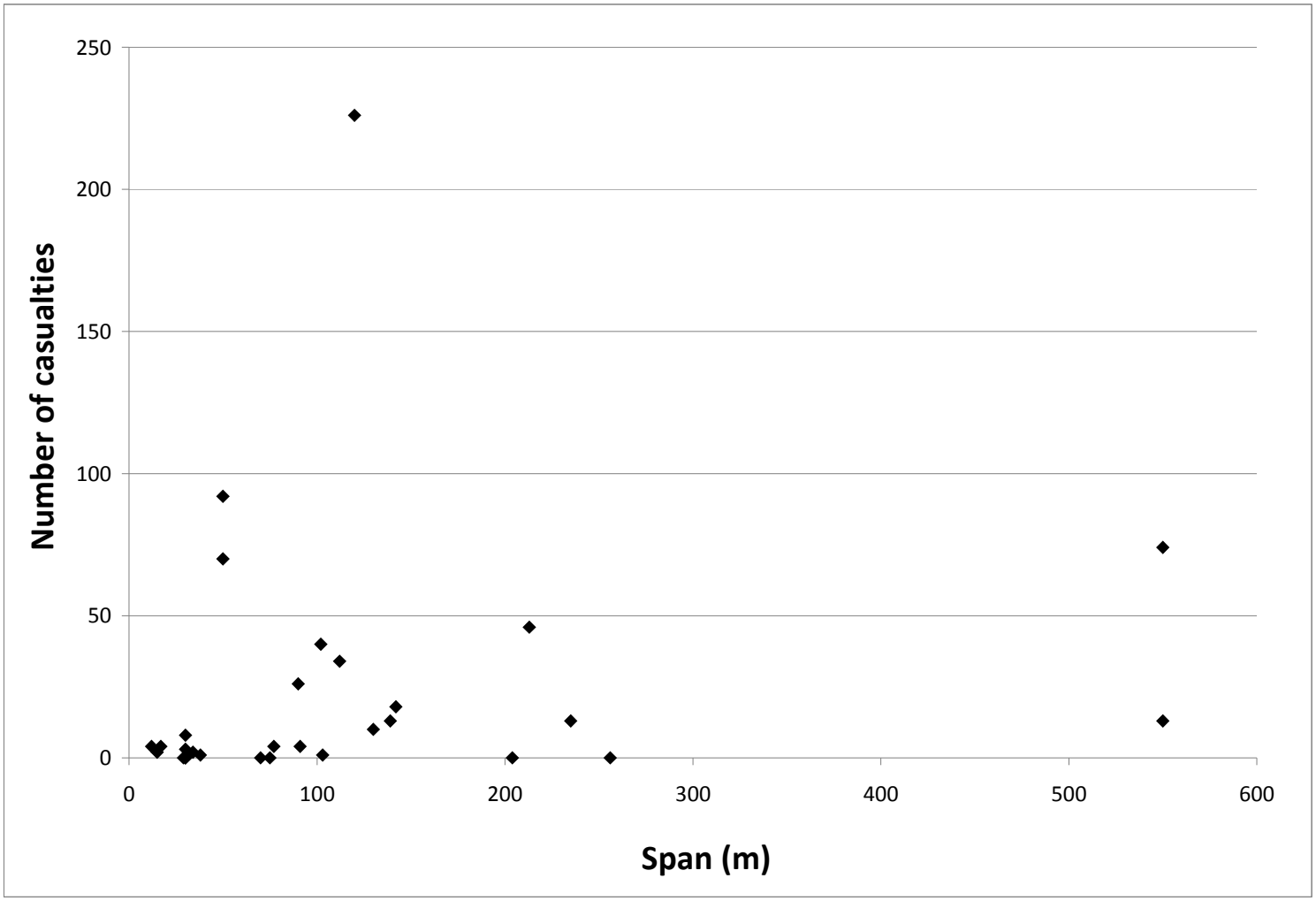
where CDF is a commuter distribution factor

CDF = 0.01 during day and night

CDF = 0.02 during commute time

- Assuming one bridge every two miles of major urban road!

Human consequences



Human consequences

Injuries

AIS	Category	Examples	MAIS % of fatality cost
0	No injury	-	-
1	Minor	Headache, single rib fracture	0.31
2	Moderate	Unconscious (<1 h), 2-3 rib fractures	4.58
3	Serious	Unconscious (1-6 h), knee dislocation	9.16
4	Severe	Unconscious (6-24 h), amputation	21.53
5	Critical (survival uncertain)	Unconscious (>24 h), pelvis crush	71.24
6	Fatal	-	100

Human consequences

- UK DfT suggests £160,000 for serious and £12,000 for light injuries (2005 prices)
- EU countries suggest €195,000 for serious and €15,000 for light injuries (2005 prices)
- RSSB suggests injury costs as a fraction of fatality costs (1/10 for major rail and 1/200 for minor rail injuries)

Human consequences

- Prediction of number and type of injuries adds further complexity
- Following the I-35W bridge collapse, majority of injuries were identified as:

  - spinal column injuries

  - burst fractures associated with vertical force-compression traumas
- All injuries determined non-critical!

Economic consequences

- Costs related to physical structural loss
  - reconstruction / repair costs
  - debris clean up
- Costs associated with reduced functionality of transportation network
  - traffic delay costs, traffic management costs
  - increased accident rates
- Costs associated with societal impact
  - business and reputation losses

Economic consequences

- Reconstruction cost will depend on:

  - type of new bridge

  - duration of reconstruction

- Commonly in literature:

  Reconstruction cost $\approx$ original construction cost

- HAZUS provides rough estimates of bridge reconstruction costs & times

Economic consequences

- Reconstruction time:

  - highway bridges: mean=230 days, st.dev.=110 days

  - railway bridges: mean=110 days, st.dev.=73 days

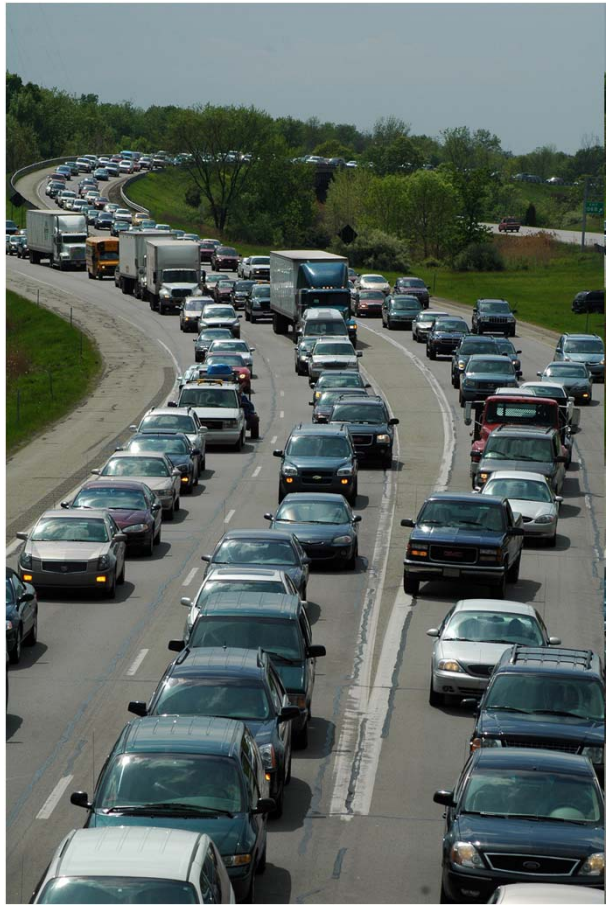
- These can be used to estimate traffic delay costs
- HAZUS also suggests repair times for different states of damage of bridges (i.e. slight, moderate, extensive)
- Debris clean up costs:

  - transportation of failed material

  - number of trucks, capacities, distance to disposal site, fuel consumption

Economic consequences

- Bridge failures cause traffic delays in the vicinity of the network
- Detours will increase total travel time
- Partial bridge failures may cause lanes closures & redistribution of traffic flows
- Value of time
- May require extensive network analysis



Economic consequences

- UK Highways Agency:
  - £9.30/hour (2002 prices) for average vehicle
- U.S. Department of Transportation
  - $8.90/person-hour for local travel
  - $12.20/person-hour for intercity travel (in 1997 prices)
  - $16.50/person-hour for trucks
- EU countries (in 1998 prices)

	Passenger Transport	**Freight Transport**
Car	Business: €21.00/person-hour Commuting/Private: €6.00/person-hour Leisure/Holiday: €4.00/person-hour	Light Goods Vehicle: €40.0/vehicle-hour Light Goods Vehicle: €43.0/vehicle-hour
Interurban Rail	Business: €21.00/person-hour Commuting/Private: €6.40/person-hour Leisure/Holiday: €3.20/person-hour	Full train load (950 tonnes): €725.0/tonne-hour Wagon load (40 tonnes): €30.0/tonne-hour Average per tonne: €0.76/tonne-hour

Economic consequences

- Traffic management costs in case of bridge repairs:
  - over or under the bridge
  - selection of scheme depends on traffic volume and road type

	Carriageway closure / full contraflow	One-lane closure	Two-lane closure
Motorway	£850 (1 km TM scheme)	£350	£450
	£1250 (3 km TM scheme)		
Dual carriageway	£500	£350	£450
Single carriageway	£800 (traffic signal control management)	£300	

Economic consequences

- Consequences on business
- Disruption of normal business activities
- Delays on customers, deliveries, suppliers
- Loss of business, increased production costs etc.
- Economic expertise is required

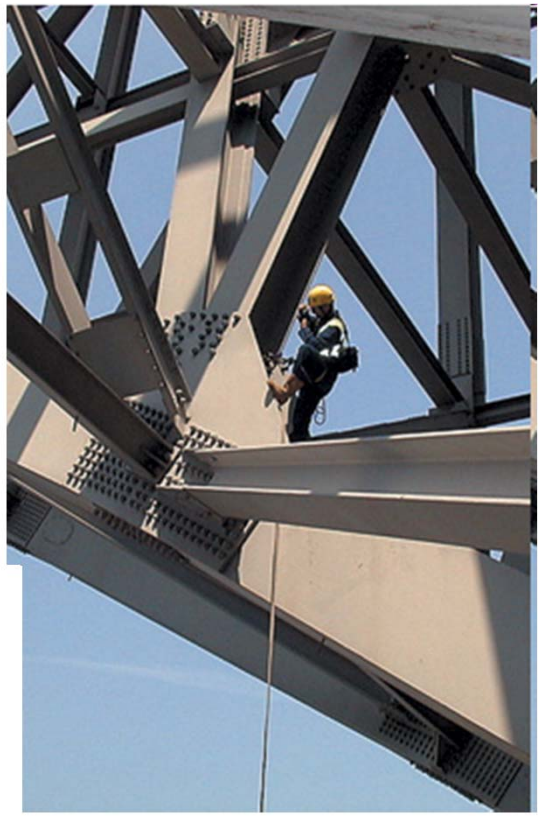
Economic consequences

- Changes in professional practice

  - strengthening or replacement of a whole class of structures

  - changes in codes of practice, development of new design rules

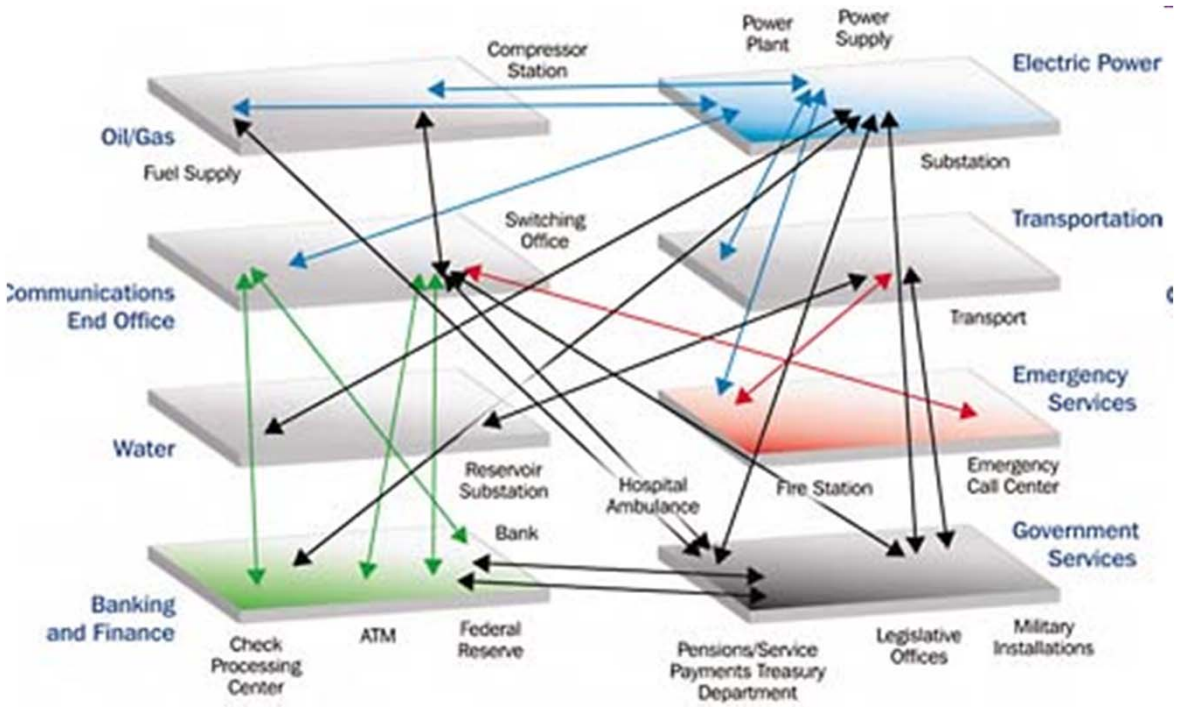
  - inspection / assessment of similar bridges



Economic consequences

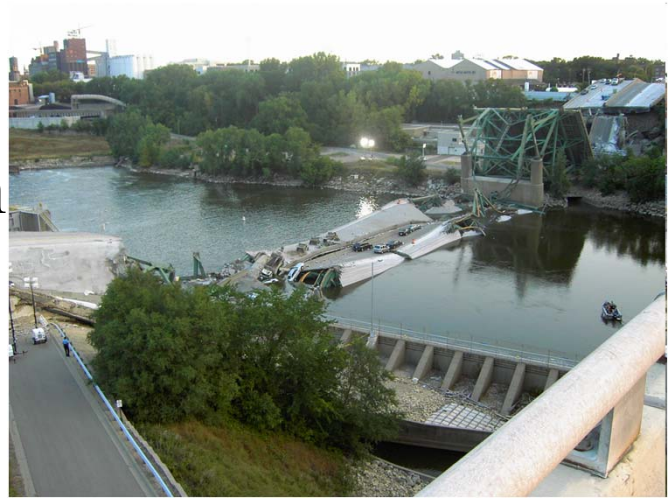
- Infrastructure interdependencies

  - bridges can be part of electricity, telephone, water, gas networks



Environmental consequences

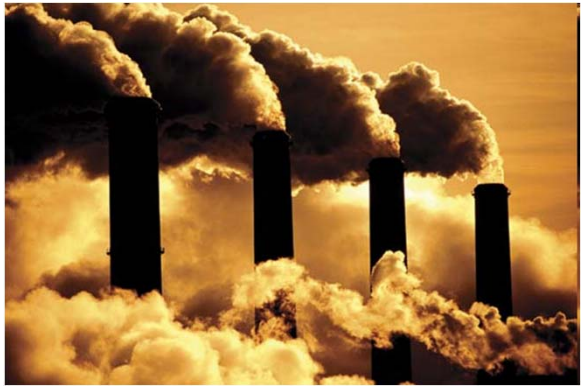
- Additional air-pollution emissions from traffic re-routing, longer travel times and distances
- Traffic congestion
- Risk of river pollution
- Emissions from site clean up and bridge re-construction
- Environmental impact usually cited in tons of carbon
- Valuation of emission costs: $0.70/ton-$590/ton of C



Environmental consequences

- Carbon emissions from production of bridge materials

Material	Carbon emitted
Steel	1820 Kg CO_2/te
Cement	800 Kg CO_2/te
Reinforced Concrete	260-450 Kg CO_2/te
Asphalt	46 Kg CO_2/te



Environmental consequences

- Emissions from traffic related sources

Vehicle type	CO_2 emissions
Petrol car	0.1730-0.2994 kg CO_2 / passenger km
Diesel car	0.1452-0.2455 kg CO_2 / passenger km
Hybrid car	0.1191-0.2173 kg CO_2 / passenger km
Light commercial van (petrol)	0.1941-0.2558 kg CO_2 / vehicle km
Light commercial van (diesel)	0.1571-0.2691 kg CO_2 / vehicle km
Heavy goods vehicle (diesel)	0.5276-1.163 kg CO_2 / vehicle km
Rail (passenger)	0.05340 kg CO_2 / vehicle km
Rail (freight)	0.02850 kg CO_2 / tonne km

Case study - Collapse of I35-W

- Built in 1964 at a cost of ~$5.2m
- ADT 140,000, ~5,700 commercial vehicles
- About 330m of its span collapsed on 01/08/2007, all within few seconds
- At the time, undergoing repair work, including replacement of top 2'' of concrete deck
- Causes of collapse:
  - design error in gusset plate dimensions
  - weight increases due to modifications
  - distribution of traffic and concentrated construction load

Case study - Collapse of I35-W

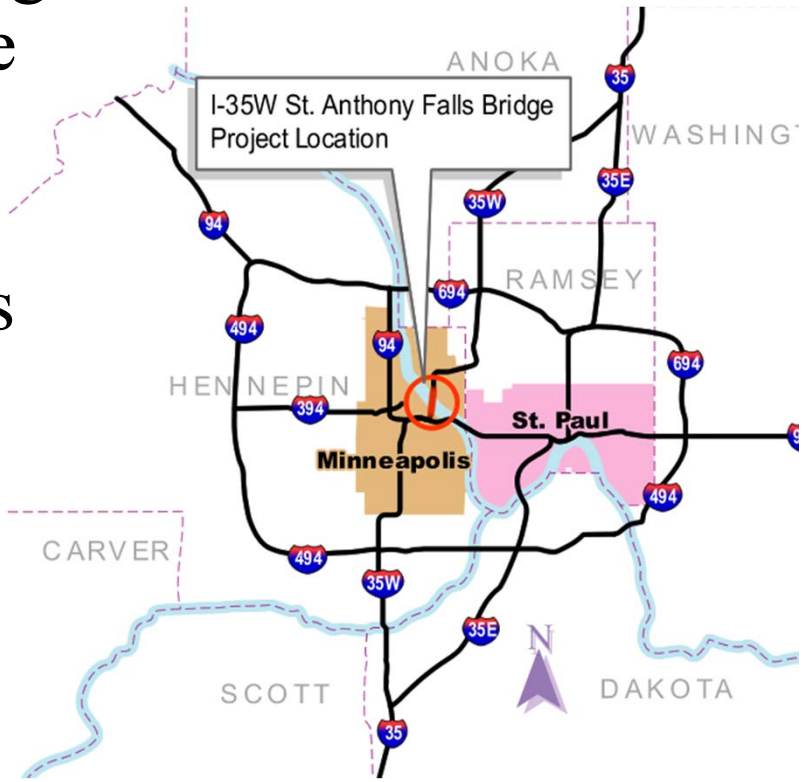
- 13 deaths, 145 injuries
- Closure of main road artery
- Cost of replacement
- Cost of detours
- Loss to regional economy
- Environmental impact
- Impact on professional practice
- Effect on public confidence

Case study - Collapse of I35-W

- New bridge completed 18/09/08, ~60 wks after collapse
- Two concrete bridges side-by-side
- Re-construction cost of ~$234m

Case study - Collapse of I35-W

- Regional econometric model using MnDoT data on ADT and vehicle mix
- Detours $400,000 per day, estimated at ~$120m over 60 wks
- Reduction of state's economic output estimated at 0.01% pa, ~$60m until replacement
- Job losses?
- Emissions?



Case study - Collapse of I35-W

- Insufficient quality control procedures
  - new checks and verifications introduced in design
- Lack of guidance with regard to placement of construction loads during maintenance and repair
  - new guidelines to be drafted and followed
- Inadequate use of inspection technology for gussets in fracture critical bridges
  - revision of inspection manuals
- Additional assessment checks for all non-load-path-redundant steel truss bridges
  - more lengthy / complex assessments
- Cost over entire US network, say in next 10 years??

Case study - Collapse of I35-W

- Risk perception: need to re-assure public
- Acceleration of rehabilitation of ‘similar’ bridges
- Reduced priority for other measures:
  - Crash protection
  - Highway improvements
- Cost of upgrading US network estimated at $140bn – how much is expedited as a result of I35W collapse?
- Additionally, what is the cost incurred from NOT undertaking other measures?
- Cost over entire US network, say in next 10 years??

Case study - Collapse of I35-W

- Casualties: ~$52m
- Cost of replacement: ~$234m
- Cost of detours: ~$120m
- Regional economic cost: ~$60m
- Traffic management costs: ~$7m
- Clean up costs: ~$8m
- Additional vehicle emissions ~$25m
- Cost from changes in professional practice, ??
- Cost from accelerated rehabilitation, ??
- Cost from not doing other things as a result, ??

- In addition:
  - Increased environmental impact
  - Job losses, permanent economic damage
  - Loss of reputation, cost of fearing the next accident

Concluding remarks

- Consequences are a fundamental component in robustness assessment
- Bridge failure consequences should be considered both in ***space*** and ***time*** domains
- Definition of system boundaries is critical
- Indirect consequences may outweigh direct consequences
- Establishing a common framework is a challenge but we now have a promising starting point

THANK YOU!

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