Transportation Systems Failure

Accidental conditions where a bridge failure occurs within the U.S., causing one fatality or greater.[1]

Data Summary

In the following table, note that the low and high likelihoods do not correspond to the low and high impacts. In addition, low and high impacts are not necessarily correlated with each other between different impact categories.

Category	Description	Metric	Low	Best	High
Health and Safety	Fatalities	Number of Fatalities[2]	1	8.6	47
	Injuries and Illnesses	Number of Injuries or Illnesses[3]	0	8.8	145
Economic	Direct Economic Loss	U.S. Dollars (2011)	$250,000[4]	$200 million[5]	$6.4 billion[6]
	Indirect Economic Loss	U.S. Dollars (2011)	See Discussion		
Social	Social Displacement	People Displaced from Home ≥ 2 Days	0[7]		
Psychological	Psychological Distress	Qualitative Bins	See Discussion		
Environmental	Environmental Impact	Qualitative Bins	N/A		
LIKELIHOOD	Frequency of Events	Number per Year[8]	0.17	0.57	2

[1] The Transportation Systems Failure hazard event is intended to include within its scope the failure of tunnels and other highway and rail infrastructure causing loss of life. However, the SNRA 2015 event is effectively scoped to bridge failure because of data availability.

[2] Low, average, and high fatalities from the set of U.S. historical bridge failure incidents in Table 3.

[3] Low, average, and high injuries from the set of U.S. historical bridge failure incidents in Table 3.

[4] DDP, generic cost estimate for state-federal bridge loss, NWS StormData preparation guide for reporting damages from natural disasters (p. B-2: Low end of $250K–$750K range selected for SNRA low estimate). National Weather Service (2007, August 17), Storm Data Preparation (Instruction 10-1605), National Oceanic and Atmospheric Administration; at http://www.nws.noaa.gov/directives/sym/pd01016005curr.pdf (retrieved 5 March 2014). This estimate does not include the other components of SNRA direct economic loss, such as business interruption.

[5] Estimate is based on information from multiple sources:
(a) Padgett, J., DesRoches, R., Nielson, B., Yashinsky, M., Kwon, O., Burdette, N., and Tavera, E. (2008). "Bridge Damage and Repair Costs from Hurricane Katrina." J. Bridge Eng., 13(1), 6–14, January/February 2008; available at http://www.owlnet.rice.edu/~jp7/Padgett_JBE_Jan08_Bridge_Damage_and_Repair_Costs_from_Hurricane_Katrina_PUBLISHED.pdf
(b) WSDOT, "I - 5 Skagit River Bridge – Estimate of the Direct Cost of Closure", accessed 3/18/2015, available at http://www.wsdot.wa.gov/NR/rdonlyres/983F3385-A349-4372-9493-1C21E033DEC0/0/SkagitRiverBridge_DirectCost_1082013.pdf.
(c) Minnesota DOT (2007, September 4), "Economic Impacts of the I-35W Bridge Collapse," available at http://www.dot.state.mn.us/i35wbridge/rebuild/pdfs/economic-impacts-from-deed.pdf (checked 15 April 2015).
(d) Pioneer Press, "The Design for the I-35W Replacement Bridge is Unveiled," available at http://www.twincities.com/ci_7122021, accessed March 18, 2015.

[6] Based upon the replacement cost of the Oakland Bay Bridge. Cuff, Dennis (2014, September 8). Cost of Bay Bridge demolition rises amid complication. *Oakland Tribune*. [$6.4 billion cost was for replacement: demolition cost estimate cited in article, $271 million.] Bay Area Toll Authority (2015). Bridge facts: San Francisco-Oakland Bay Bridge [dynamic resource]: http://bata.mtc.ca.gov/bridges/sf-oak-bay.htm (retrieved 13 April 2015).

[7] Social displacement was assumed to be zero for the Transportation Systems Failure national-level event.

[8] Low, best, and high frequencies represent the inverse of the longest inter-arrival time (gap) between incidents, the average number of incidents per year, and the largest number of incidents occurring in any one year from the set of U.S. historical bridge failure incidents in Table 3.

Event Background

The SNRA Transportation Systems Failure hazard event was originally developed by the DHS National Protection and Programs Directorate (NPPD) for the 2012–13 Homeland Security National Risk Characterization (HSNRC) project.[9] The original HSNRC data and analysis were expanded and revised for the 2015 SNRA by project staff from Argonne National Laboratory and FEMA.

Transportation infrastructure is broadly distributed, but the health of the overall system can be monitored by the state of disrepair and trends of failures of bridges, tunnels, road segments, and other assets. Bridges and tunnels are necessary means to overcome physical obstacles. By necessitating greater convergence of traffic in these locations, bridges and tunnels become critical nodes or choke points in networks. However, roadways can also operate as critical nodes when they provide sole or primary access to an area, connect to critical facilities, or when there is a lack of sufficient redundancy within the network.

Infrastructure owners and operators often struggle to fund and implement proper maintenance and repairs to the structures and assets that compose transportation systems, leading to an increasing risk of infrastructure failure. The Nation's transportation network includes reliance on key infrastructure nodes such as bridges and tunnels, which are aging. In some cases these nodes are at risk due to conditions exceeding design specifications, and in others due to external threats and hazards. The more aware owners and operators are of the critical nature of their key nodes, the more likely they are to maintain them appropriately. However, the general system decline and lack of resources suggests a broader trend toward increasing infrastructure failure.[10]

Transportation system failures can disrupt supply chains, resulting in unexpected costs to repair or rebuild damaged components. They can also increase transportation costs to those normally using the disrupted facility due to increased congestion or detouring, and often entail delays for emergency response and other important services. In rare instances these infrastructures can come under extreme loads or other unforeseen conditions (e.g., design errors), that create situations where high numbers of casualties could occur from their catastrophic failure.

Bridges, tunnels, and roadway culverts represent a subset of transportation infrastructure assets that, as identifiable network nodes and through interaction with the surrounding environment, are at a greater risk to acute failures that can cause broader disruption or impact to the transportation system. A background summary of bridge, tunnel, and culvert transportation failures are summarized below.

Bridge Failures

Bridge failures represent a subset of all transportation risk; however, there is a larger amount of data on highway bridge condition and failures compared with other transportation infrastructure, which better enables a national-level assessment of associated risks. The National Bridge Inventory (NBI) maintains condition and inspection data on individual bridges for all roadway bridges in the U.S. There is no national database of highway bridge failures; however, a review

[9] The HSNRC was a collaborative effort of the DHS analytic enterprise to expand the 2011 SNRA risk knowledge base to additional threats and hazards, and to adapt the SNRA to the information needs of DHS strategic planning.
[10] One advocacy group assessed that the number of bridges older than 50 years was 95,150 in 1990 and 199,584 in 2010, and would be 383,060 by 2030 and 542,170 by 2050. Transportation for America (2011), "The Fix We're In For: The State of Our Nation's Bridges," Washington, DC. Accessed 3/18/2015 http://t4america.org/docs/bridgereport/bridgereport-national.pdf.

of 92 failures[11] has categorized causes of bridge failure as indicated in Table 1. This failure database was statistically analyzed in conjunction with the NBI to estimate that annually, 128 bridges fail in the U.S. It should be noted, however, that this is a statistically determined number, and includes all bridge failures (i.e., from major roadways to low-volume roads), some of which may have little impact. Most failures are a result of flooding or scour (a hydraulic-related failure of bridge foundation supports) as well as truck or vehicle collisions. Deterioration, fatigue, fire, soil bearing, and bridge overload have also resulted in bridge failures.

Databases of condition and inspection information to the NBI are not broadly available for railway bridges. Although rail bridges are of systemic and economic importance, they are primarily privately owned facilities, and therefore, national data is not maintained in a central location. The potential for high casualty counts resulting from rail bridge accidents may be attributable to passengers trapped in trains, as well as momentum of the train following the incident.

The Bridge Forum Bridge Collapse Database, maintained by the Cambridge University Department of Engineering, contains 25 U.S. road, rail, and pedestrian bridge failures that resulted in one or more fatalities from 1964 through 2007 (Table 3).[12] This database has been updated with information from multiple data sources, and has been used to provide a basis for the frequency, fatality, and injury estimates in the 2015 SNRA.

Table 1: Bridge Failure Study, Percentages of Failure Causes

Cause of Failure	Partial Collapse	Total Collapse	Total Count	Percentage of Total
Hydraulic Total	21	27	48	52.17%
Hydraulic	–	2	2	2.17%
Flood	8	18	26	28.26%
Scour	12	7	19	20.65%
Ice	1	–	1	1.09%
Collision Total	17	1	18	19.57%
Collision	14	1	15	16.30%
Auto/Truck	3	–	3	3.26%
Overload	3	8	11	11.96%
Deterioration Total	4	2	6	6.52%
Deterioration	–	1	1	1.09%
Steel deterioration	2	1	3	3.26%
Concrete deterioration	2	–	2	2.17%
Fire	3	–	3	3.26%
Construction	1	1	2	2.17%
Fatigue-steel	1	–	1	1.09%
Bearing	–	1	1	1.09%
Soil	1	–	1	1.09%
Miscellaneous	1	–	1	1.09%
Total	52	40	92	100.00%

[11] Reproduced from Table 2, p. 27: Cook, W. (2014, May 1). "Bridge Failure Rates, Impacts, and Predictive Trends." Doctoral Dissertation, Department of Civil & Environmental Engineering, Utah State University, Logan, UT: at http://digitalcommons.usu.edu/etd/2163/ (checked 13 April 2015).

[12] Imhof, Daniel, and University of Cambridge (2012). BridgeForum Bridge Failure Database [electronic resource]. Structures Group, University of Cambridge Department of Engineering, adapted from Imhof, Daniel (2005), Risk Assessment of Existing Bridge Structures [dissertation], abstract at http://www-civ.eng.cam.ac.uk/abstract/Imhofabs.html. Database at http://www.bridgeforum.org/dir/collapse/country/United%20States.html (accessed December 13, 2012). The 25 incidents causing fatalities are a subset of 71 U.S. bridge failure incidents from 1964–2007 in total in these sources.

Tunnel Failures[13]

In the United States, there are about 337 highway tunnels as compared to over 600,000 highway bridges. As with bridges, many of these tunnels are choke points or critical nodes in the Nation's highway transportation network that have completely unique design, construction, and operational requirements. Tunnel structures are designed to withstand environmental impacts from the soil or seabed through which they pass; however, a failure of a tunnel could result in hundreds of casualties and billions of dollars in reconstruction cost. The greatest threats to tunnel users are fire and chemical spills, resulting from the closed environment of tunnels. Therefore, life safety and evacuation are the most important considerations for risk reduction. There have been a number of tunnel incidents in the United States, which resulted in casualties, but these incidents have not been as catastrophic as compared to those in other countries. Tunnel owners must conduct systematic reviews to understand their facilities and vulnerabilities, and develop protection and life safety strategies.

There is no national data set or study that presents tunnel failure risks or vulnerabilities in the U.S. Global studies have been conducted;[14] however, variability in international design and safety practices relating to construction, operation, and management suggest that global trends in tunnel failures may not accurately represent or be predictive of such failures in the United States.

Culvert Failures

The number of culverts in the U.S. is significantly greater than the number of bridges, and most of these are roadway culverts that are owned and maintained by state Departments of Transportation (DOT), state Departments of Natural Resources, and local counties or municipalities. Culverts are water runoff control devices designed to constrict or control surface water runoff to allow it to pass under roadways, railways, or other similar systems. Culverts range in size from small pipes several inches in diameter to large structures that may be dozens of feet wide. They are distinct from bridges in that they contain structure on all sides of the opening (although some newer "open-bottomed" culverts omit structure on the bottom of the opening to preserve streambeds), and can be constructed of concrete, galvanized steel, aluminum, timber, or other materials. As with bridges and tunnels, however, the flooding, failure, or washout of a roadway culvert results in closure of, or disruption to, the overlying roadway.

The cost and length of time to replace or repair a road culvert is significantly less than bridges and tunnels; therefore, the aggregate risks associated with disruption may be comparatively less than that for bridges. Road culvert failures typically occur during extreme weather events, heavy rains, and flooding. They frequently are a result of overwhelmed capacity, poor maintenance, or some combination thereof. Numerous state DOTs maintain inventories of culvert condition and inspection data; however, such practices are not nationally standardized and are documented with a widely ranging level of detail, if at all.[15,16]

[13] Transportation Research Board (TRB), National Academies (2006). "TCRP Report 86/NCHRP Report 525, Transportation Security, Volume 12: Making Transportation Tunnels Safe and Secure," National Academies Press, Washington, DC. At http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_525v12.pdf (checked 13 April 2015).

[14] For example, "Catalog of Notable Tunnel Failure Case Histories (Up to October 2012)," Presented by Mainland East Division, Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong: at http://www.cedd.gov.hk/eng/publications/geo/doc/HK%20NotableTunnel%20Cat.pdf (accessed 16 March 2015).

[15] Wall, T.A. (2013) "A Risk-Based Assessment Tool To Prioritize Roadway Culvert Assets for Climate Change Adaptation Planning," Doctoral Dissertation, School of Civil & Environmental Engineering, Georgia Institute of Technology, Atlanta, GA: at https://smartech.gatech.edu/handle/1853/50393 (checked 13 April 2015).

Added 2015

Data Scope

The SNRA transportation systems failure data set includes historical incidents of automotive, rail, and pedestrian bridge collapses in the United States. Bridge failures represent a subset of all mass transportation risk. However, there is a larger amount of data on bridge failures compared with tunnel and other transportation infrastructure, and bridges were considered sufficiently representative of a larger trend of changing conditions in critical infrastructure for the purposes of informing preparedness planning decisions at a strategic level.

Assumptions

- Transportation-related infrastructure such as tunnels, roadway culverts, navigation locks, and railway systems are all potential points of system vulnerability and failure. However, due to lack of national-level data to serve as a basis for a nationally-consistent risk assessment, these systems are excluded and the focus is redirected exclusively to bridges. Additionally, focus is given to major roadway bridges (i.e., those located on main highway and roadway networks), and excludes bridges such as those on undeveloped roads (e.g., logging, forest access) or private property.
- The SNRA social displacement measure (persons, other than response personnel and those hospitalized, with homes destroyed or who are prevented from returning home for more than two days) is used in this analysis. Other measures, such as whether or not a transportation system component provides soleaccess to a community or facility, or network redundancy can be useful alternative metrics for social displacement, but are excluded here due to lack of available national-level data.
- Aging infrastructure, whose construction techniques and materials are now considered substandard in the U.S., are considered part of the failing transportation infrastructure system if they had continued to be used at the time of their failure.
- Economic impacts are highly varied and dependent on the context of the particular bridge failure and its cascading effects. There is no basis to make such an estimate in this assessment for the more minor failures in an unclassified estimate. Therefore, direct costs reflected in the quantitative estimates, and a discussion of other relevant factors, including broader and indirect economic impacts, are provided in the final section.
- While there is no broad consensus as to what items to include in a list of U.S. bridge failures—the factors that most directly contributed to those risks, or in the analysis of their impacts—the resources consulted and discussed here provide a sufficient basis upon which to form an estimate and inform further consideration, but not a comprehensive and complete study of those failures, contributing factors, or impacts.

Frequency

Low, best, and high estimates of annual frequency represent the inverse of the longest inter-arrival time (longest gap between incidents, six years, 1995–2001), the average number of incidents per year, and the maximum number of incidents occurring in any one year of the incidents in Table 3.

[16] Federal Highway Administration (FHWA) (2014). “Culvert and Storm Drain Management Case Study: Vermont, Oregon, Ohio, and Los Angeles County.” U.S. Department of Transportation, Washington, D.C.

Health and Safety

Low, best, and high estimates of fatalities and injuries represent the lowest, average, and highest fatalities and injuries from the set of incidents in Table 3.

Direct Economic Loss

Direct economic impacts as defined in the SNRA include decontamination, disposal, and physical destruction costs including property (structure, contents, physical infrastructure and other physical property) and crop damage; one year's lost spending due to fatalities; medical costs; and business interruption directly resulting from the impacts of an event.

The historical incident database (Table 3) did not report economic damage information. Low, best, and high estimates for the SNRA 2015 Transportation Systems Failure hazard event are based upon literature data and analyst judgment.

The low estimate of direct economic loss is based on a generic cost estimate for state-Federal bridge loss for reporting damages from natural disasters.[17] This estimate does not include the other components of SNRA direct economic loss, such as business interruption.

For the best estimate of direct economic loss, cost information available for three recent events—bridges affected by Hurricane Katrina, the I-35W Bridge, and the I-5 Skagit River Bridge—was used to compute an average cost including the impact on transportation costs, and economic output, where available.[18] Because these estimates include costs in addition to physical damage, their degree of approximation to the SNRA direct economic loss metric (which includes a component for direct business interruption but not other second-order costs) is unknown. The SNRA project team made the assumption that the resulting average would be a reasonable approximator to an average cost of catastrophic bridge failures resulting in loss of life, within the order of magnitude precision of the SNRA.

The cost for replacing the Oakland Bay Bridge was used as the high estimate for direct economic loss.[19] Note that this estimate excludes the impact on transportation costs, output, and employment, and therefore underestimates both direct and total economic loss from this event.

Social Displacement

The impacts of transportation network disruptions on travel behavior are a function of the geographic scope of the disruption, the existence of alternate routes, network redundancy, capacity utilization, and congestion, and restoration time. Depending on the level of disturbance, travelers may consider options such as shifting work schedules, telecommuting, or public transportation.

[17] National Weather Service (2007, August 17), Storm Data Preparation (Instruction 10-1605), National Oceanic and Atmospheric Administration; at http://www.nws.noaa.gov/directives/sym/pd01016005curr.pdf (retrieved 5 March 2014). Page B-2: Low end of $250K–$750K range selected for SNRA low estimate.

[18] Estimate is based on information from multiple sources:
(a) Padgett, J., DesRoches, R., Nielson, B., Yashinsky, M., Kwon, O., Burdette, N., and Tavera, E. (2008). "Bridge Damage and Repair Costs from Hurricane Katrina." J. Bridge Eng., 13(1), 6–14, January/February 2008; available at http://www.owlnet.rice.edu/~jp7/Padgett_JBE_Jan08_Bridge_Damage_and_Repair_Costs_from_Hurricane_Katrina_PUBLISHED.pdf
(b) WSDOT, "I - 5 Skagit River Bridge – Estimate of the Direct Cost of Closure", Accessed 3/18/2015, available at http://www.wsdot.wa.gov/NR/rdonlyres/983F3385-A349-4372-9493-1C21E033DEC0/0/SkagitRiverBridge_DirectCost_1082013.pdf.
(c) Minnesota DOT (2007, September 4), "Economic Impacts of the I-35W Bridge Collapse," available at http://www.dot.state.mn.us/i35wbridge/rebuild/pdfs/economic-impacts-from-deed.pdf (checked 15 April 2015).
(d) Pioneer Press, "The Design for the I-35W Replacement Bridge is Unveiled," available at http://www.twincities.com/ci_7122021, accessed March 18, 2015.

[19] Cuff, Dennis (2014, September 8). Cost of Bay Bridge demolition rises amid complication. *Oakland Tribune*. [$6.4 billion cost was for replacement: demolition cost estimate cited in article, $271 million.] Bay Area Toll Authority (2015). Bridge facts: San Francisco-Oakland Bay Bridge [dynamic resource]: http://bata.mtc.ca.gov/bridges/sf-oak-bay.htm (retrieved 13 April 2015).

For the purposes of the SNRA, social displacement was defined as the number of people forced to leave home for a period of two days or longer. Note that there are limitations to this measure of social displacement, as the significant differences between temporary evacuations and permanent displacement due to property destruction are not captured.

The historical incident database (Table 3) did not include information on persons displaced. The SNRA project team made the assumption that no persons were separated from their homes for more than two days for any of these incidents.

Psychological Distress

Psychological impacts for the SNRA focus on significant distress and prolonged distress, which can encompass a variety of outcomes serious enough to impair daily role functioning and quality of life. An index for significant distress was created that reflected empirical findings that the scope and severity of an event is more important than the type of event.[20] The equation for this index uses the fatalities, injuries, and displacement associated with an event as primary inputs. A multiplicative factor elicited from subject matter experts (SMEs) weights the index for differing psychological impact based on the type of event, but as a secondary input.

The Significant Distress Index is calculated from these inputs using a formula proposed by subject matter experts consulted for the SNRA project: $N_{SD} = C_{EF} \times (5\ Fat + Inj + \frac{1}{2}\ D)$, where N_{SD} represents the number of persons significantly distressed, C_{EF} is the expert assessed Event Familiarity Factor, *Fat* is the number of fatalities, *Inj* is the number of injuries and/or illnesses, and *D* is the number of persons displaced (Social Displacement).

- In words, this formula suggests that there are 5 significantly distressed persons for each life lost; 1 for each person injured; and 1 for each 2 people displaced. This formula was constructed to reflect the empirical finding that the most severe stressor of a disaster is losing a loved one, followed by injury, followed by displacement.
- The Event Familiarity Factor is intended to capture the extent to which the event entails an ongoing threat with uncertainty regarding long-term effects, is unfamiliar, or that people dread, exacerbating psychological impacts. This factor, ranging from 1.0 for familiar events to 1.3 for unfamiliar events, was provided by SMEs for each national-level event included in the SNRA.
- Uncertainty was captured by applying the index formula to the low, best, and high estimates of these three human impact metrics.

The numerical outputs of this index formula were used to assign events to bins of a risk matrix for a semi-quantitative analysis of psychological risk in the SNRA.

The Transportation System Failure national-level event was added by the SNRA project subsequent to the 2011 iteration of the SNRA for which Event Familiarity Factors were elicited from SMEs. The SNRA project team assigned a provisional Event Familiarity Factor of 1.0 by analogy with the SNRA Dam Failure event, for the calculation of *provisional* psychological distress estimates. It must be stressed that this assignment has not been reviewed by the 2011 SMEs.

[20] See Appendix G for references and additional discussion of the SNRA Psychological Distress metric.

Environmental Impact

In general, the direct environmental impacts of a bridge collapse would be limited to localized debris and disturbance of contaminants in a riverbed. In special cases, where environmentally volatile or hazardous material is transported over the bridge (either by vehicles or by co-located infrastructure such as fuel pipelines), direct environmental impacts would be greater. Indirect environmental impacts related to additional emissions related to increased congestion and detouring as a result of disruption, and direct impacts to the surrounding environment related to replacement activities could also occur. However, these are significantly variable and contextual, and thus difficult to reasonably quantify.

The environmental impact estimate, which was assessed for the 23 original national-level events of the 2011 SNRA by subject matter experts from the U.S. Environmental Protection Agency (EPA), could not be assessed for the transportation systems failure event added to the SNRA in calendar year 2015. A future iteration of the SNRA will assess the environmental impacts of this event.

Potential Mitigating Factors

The aging of the Nation's transportation infrastructure is a risk that can be addressed through proactive inspection, maintenance, repair and replacement of deteriorating assets. However, this would require significant investment at the local, state, and Federal levels, and, therefore such activities will have to be prioritized based on criticality, risk, available funds, and other factors. A recent Federal requirement that state DOTs engage in risk-based asset management[21] to better strategically plan for transportation infrastructure investment and improvement may ensure more effective use of existing funding, but expanded funding may also be required for effective mitigation of risk. Additionally, complementary action may be taken for enhanced contingency, response, and emergency preparedness planning. In the event of a transportation system failure, better emergency preparedness and response planning will enable agencies to more immediately respond to and mitigate direct impacts, and better contingency planning (e.g., establishing detouring and rerouting plans around higher risk assets) can mitigate indirect costs associated with disruption to the transportation system and supply chain, and associated congestion.

Additional Relevant Information

There is not a comprehensive database for bridge, tunnel, or culvert failures in the U.S. There is also a lack of consensus on how to define a failure, with some studies excluding failures due to natural disasters.[22]

The SNRA does not quantitatively assess trends or other measures of how the current national risk picture may be changing. However, engineering design principles, coupled with NBI bridge inspection data do provide potential indicators of increased vulnerability or risk of failure among bridges in the United States. These are summarized below.

Bridge Condition Indicators Related to Increased Risk of Failure

Scour-Critical Bridges: Scour refers to the "removal of a streambed or bank area by streamflow; erosion of streambed or bank material due to flowing water; often considered as being localized

[21] Moving Ahead for Progress in the 21st Century Act (MAP-21), U.S. Public Law 112-141 – July 6, 2012

[22] Wardhana, Kumalasari and Hadpriono, Fabian C., "Analysis of Recent Bridge Failure in the United States," *Journal of Performance of Constructed Facilities*, 2003, Vol 17(3), pp. 144–150.

around piers and abutments of bridges."[23] Scour critical bridges are those that either have insufficient information regarding the construction of the bridge's substructure (i.e., bridge foundation)[24] or that are known to have a substructure or foundation element that has structural issues or is determined to be unstable due to scouring. Scour-critical bridges are not necessarily substandard and do not note a specific defect for the structure; they are simply structures that should be monitored during high water events as they may be more susceptible to settlement and foundation failure if scouring of the stream or river would occur during a high water event.

Fracture-Critical Bridges: These are bridges that do not contain redundant supporting elements, and if key supports fail, the bridge would be in danger of partial or complete collapse.[25] Fracture criticality does not necessarily mean that a bridge is inherently unsafe, but rather that the design lacks redundancy and, therefore, may be at greater risk to threats that could damage fracture critical members of the structure.

Functionally Obsolete Bridges: These are bridges built to design standards that are no longer in use. For example, they may not have adequate lane widths, shoulder widths, or vertical clearances to serve current traffic demand. These bridges are not inherently unsafe and are not automatically rated as structurally deficient; however, in some cases they may have different operational or management requirements (e.g., imposing weight or clearance restrictions).

Structurally Deficient Bridges: These are bridges "where significant load carrying elements are found to be in poor or worse condition due to deterioration and/or damage, or the adequacy of the waterway opening provided by the bridge is determined to be extremely insufficient to the point of causing intolerable traffic interruptions" (i.e., the deck is frequently overtopped by water during floods). These structures are classified as structurally deficient if the deck, superstructure, substructure, or a culvert is rated in "poor" condition (0 to 4 on the NBI rating scale).[26]

Fatalities, Injury and Illness Related to Bridge Failures

The deadliest failure of a bridge used for automobile transportation in the United States since 1960 was the collapse of the Silver Bridge over the Ohio River in 1967, which killed 46 people and injured at least nine. The bridge collapsed due to the failure of a single fracture-critical structural bridge member due to fatigue. Another recent major failure of a fracture-critical bridge was the collapse of the I-35W Bridge in Minneapolis in 2007, which killed 13 people with 145 injured. The failure in this latter case was the result of a structural member gusset plate that was constructed thinner than was specified in the original design and ripped along a line of rivets. A truss railroad bridge in Mobile, Alabama, in 1993 failed leading to 47 deaths and 103 injuries. This failure was caused when an assembly of heavy barges had collided with the bridge just eight minutes prior to the failure, causing displacement of a bridge span and deformation of the rails.

Economic Impact Studies of Bridge Failures

Little analysis has been conducted of the economic impacts from bridge failures, and the economic impacts of such incidents are highly contextual. They must consider the full range of systemic impacts of the incident. The National Infrastructure Simulation and Analysis Center

[23] FHWA (2012). "Bridge Inspector's Reference Manual." U.S. Department of Transportation, Washington, D.C.
[24] Marathon County Highway Department (2015), "Scour Critical Bridges." Accessed 3/17/2015, http://www.co.marathon.wi.us/Departments/HighwayDepartment/LocalGovernmentInformation/ScourCriticalBridges.aspx.
[25] AASHTO (Undated) "Subcommittee on Transportation Communications: Bridge Terms Definitions." Accessed 3/17/2015, http://www.iowadot.gov/subcommittee/bridgeterms.aspx#f.
[26] MDOT (2015) "Structurally Deficient." Accessed 3/17/2015. At http://www.michigan.gov/mdot/0,4616,7-151-9618_47418-173622--,00.html.

(NISAC) conducted an analysis of the consequences of the failure of the I-35W Bridge in Minneapolis, Minnesota, in 2007.[27] The estimated cost for reconstruction ranged from $40 million to $180 million, pending decisions about whether only damaged sections would need to be replaced, or the entire bridge. The broader economic impacts were not assessed, but the cascading impacts to infrastructure provide insights into the source of economic losses that might result from the loss of a significant bridge. For example, the primary economic impact of the loss of the I-35W bridge was assessed to be the increased commuting times and transportation delays related to the 140,000 cars/day that would need to be rerouted. Changes for trucking would create minor increases in transit time for goods shipments going through the Twin Cities metropolitan area. While there were negligible impacts to the water and wastewater infrastructures in this incident, bridge infrastructures frequently include co-located water pipelines, power lines, fiber-optic cables, and sometimes fuel pipelines, which could be damaged in such an event. There were no such complications in the collapse of the I-35W Bridge. However, the failure of a bridge that included damage to these other infrastructures would have had a much more significant multi-sector systemic impact than what was observed in I-35W.

The Minnesota DOT (MNDOT) analyzed the impact of the loss of the bridge on road users and the Minnesota economy. The increased cost to road users totaled $400,000 per day in terms of longer travel times and higher operating costs for auto ($247,000) and commercial truck traffic ($153,000). These increased transportation costs were assessed to have a direct impact on businesses in the Minneapolis area. The economic costs in terms of state gross domestic product were estimated to be $113,000 per day, with a total impact of $60 million over the 2007–2008 restoration period.[28] MNDOT estimated that the total replacement project would cost $393 million dollars.[29]

The 26-day closure of the I-5 Skagit River Bridge in Washington State was estimated by the Washington State DOT to have had a direct economic impact on travel costs of $8.3 million.[30] The analysis included estimates for increases in variable operating costs and travel times due to rerouting of traffic during bridge restoration. The total cost of the bridge replacement was $20.7 million, with $8.1 million for the temporary bridge, $8.5 million for the new permanent bridge, and $4.1 million for additional repair work to other parts of the bridge

The significant damage to highway bridges along the coastal region of Louisiana, Mississippi, and Alabama caused by the combination of high winds, rain, and storm surge in Hurricane Katrina led to an estimated cost to repair or replace the damaged bridges at over $1 billion. Much of the bridge damage from Katrina is attributable to storm surge resulting in damage to mechanical and electrical equipment on movable spans and displacement of bridge decks in traditional fixed spans. The average repair/replacement cost for bridges damaged in Hurricane Katrina was estimated to be $14 million, ranging from $1,000 for minor repairs to mechanical systems for movable bridges in Louisiana, to an estimated $276 million for repairs to US-90 in Mississippi.[31] Table 2 shows the estimated cost by extent of bridge damage.

[27] National Infrastructure Simulation and Analysis Center, "Impacts of the I35W Bridge Failure (Preliminary Analysis)," August 3, 2007.
[28] Minnesota DOT (2007, September 4), "Economic Impacts of the I-35W Bridge Collapse," available at http://www.dot.state.mn.us/i35wbridge/rebuild/pdfs/economic-impacts-from-deed.pdf (checked 15 April 2015).
[29] Pioneer Press, "The Design for the I-35W Replacement Bridge is Unveiled," available at http://www.twincities.com/ci_7122021, accessed March 18, 2015.
[30] WSDOT, "I - 5 Skagit River Bridge – Estimate of the Direct Cost of Closure," accessed 3/18/2015. http://www.wsdot.wa.gov/NR/rdonlyres/983F3385-A349-4372-9493-1C21E033DEC0/0/SkagitRiverBridge_DirectCost_1082013.pdf.
[31] Padgett, J., DesRoches, R., Nielson, B., Yashinsky, M., Kwon, O., Burdette, N., and Tavera, E. (2008). "Bridge Damage and Repair Costs from Hurricane Katrina." *Journal of Bridge Engineering* 13(1), 6–14, January/February 2008.

The repair costs to bridges with more minor damage from Hurricane Katrina amounted to less than $10,000; however, there was significant variation in the repair cost for bridges that were in the extensive and complete damage state, ranging from $25,000 to nearly $276 million. Repair costs are a function of many different factors including size of bridge, how many of the spans were collapsed, whether or not the bridge was salvageable or required replacement, as well as the level of damage to and cost for repair of the submerged electrical and mechanical systems.[32]

Table 2: Estimated Bridge Repair or Replacement Cost Following Hurricane Katrina[33]

Bridge Damage	Number of Bridges	Minimum	Average	Maximum
Slight-Moderate	19	$1,000	$374,737	$6,000,000
Extensive	20	$25,000	$1,893,250	$7,700,000
Complete	5	$1,500,000	$116,880,000	$276,000,000
Total	44	$1,000	$14,304,205	$276,000,000

[32] Ibid.
[33] Ibid.

Table 3: Major Bridge Failures (SNRA Data Set)

Event	Year	Fatal	Injured	Displaced > 2 Days
Lake Pontchartrain Bridge	1964	6	0	0*
Silver Bridge (Ohio River)	1967	46	9	0*
Sidney-Lanier Bridge (Brunswick, GA)	1972	10	0	0*
Motorway Bridge (Pasadena, CA)	1972	6	0	0*
Lake Pontchartrain Bridge	1974	3	0	0*
21-Span Pass Manchac Bridge (LA)	1976	2	2	0*
Sunshine Skyway Bridge (St. Petersburg, FL)	1980	35	0	0*
Multiple Span (East Chicago, Indianapolis)	1982	13	18	0*
Syracuse Bridge (NY)	1982	1	5	0*
Connecticut Turnpike Bridge (Greenwich)	1983	3	3	0*
Walnut St. Viaduct (Denver, CO)	1985	1	4	0*
El Paso Bridge (TX)	1987	1	7	0*
Oakland Bay Bridge (San Francisco, CA)	1989	1	0	0*
Truss Bridge (Mobile, AL)	1993	47	0	0*
Truss Bridge (Concord, NH)	1993	2	7	0*
Interstate 5 (Coalinga, CA)	1995	7	0	0*
3-Span 3-Girder (Clifton)	1995	1	0	0*
Queen Isabella Causeway (TX)	2001	8	0	0*
Marcy Bridge (Utica-Rome Expressway)	2002	1	9	0*
Highway 14 Overpass (TX)	2002	1	1	0*
Imola Avenue Bridge (Napa, CA)	2003	1	7	0*
Interstate 70 Bridge (Denver, CO)	2004	3	0	0*
Shelby (NC)	2004	1	2	0*
35-West Bridge (Minneapolis, MN) [34]	2007	13	145	0*
MacArthur Maze[35]	2007	1	0	0*

[34] Fatality and injury data for the significant I-35W bridge collapse (2007) were obtained from Hao, S. (2010), I-35W bridge collapse, *Journal of Bridge Engineering* (September/October 2010) 608-609, at http://suhao-acii.com/files/I35W_note.pdf (retrieved January 2013).
[35] Waters, Lew (2014). Bridge collapses in the U.S. from 1940 to 2013. Internet resource (not academic or peer reviewed). At http://lewwaters.files.wordpress.com/2013/06/bridge-collapses-in-the-u-s-from-1940-to-2013.pdf (retrieved 15 April 2014).

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