# ASSESSING RISK FOR BRIDGE MANAGEMENT

# FINAL REPORT

*Prepared for:*

AASHTO Standing Committee on Highways

NCHRP 20-07/Task 378

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# NCHRP 20-07 Task 378 Final Report

## Contents

## EXECUTIVE SUMMARY


Western Management and Consulting (WMC), Countermeasures Assessment and Security Experts (CASE™) and Paul D. Thompson conducted research with the objective:

> *to develop proposed AASHTO guidelines for a data-driven risk assessment at the bridge and structure level. At the minimum, the guidelines should consider risks from natural and man-made hazards and should be suitable for use in a bridge management system.*

The research effort focused on developing guidelines for a data-driven risk assessment at the bridge and structure level that considered risks from natural and man-made hazards. The essence of this effort was to identify needs of DOTs and articulate in a proposed AASHTO guidance document what data, tools and methods will address those needs.

In many state transportation agencies, risk management and asset management historically have been two distinct professional disciplines, each with its own data, techniques, jargon, and management methods. The premise of these Guidelines is that parts of risk management can be incorporated into asset management, so that risk concerns can be fully and appropriately considered in decisions about project priorities, resource allocation, and performance management.

A key requirement for the Guidelines is that they can be implemented with the aid of bridge management systems. Bridge management systems (BMS) typically provide functions to capture inventory and inspection data for each bridge, and then provide a set of mathematical models to analyze each bridge to forecast future conditions, performance, and costs. Most fully-developed bridge management systems compute project benefits using a life cycle cost analysis. In some cases, this life cycle cost analysis can include the user costs associated with functional deficiencies. Risk assessment that is fully integrated with this BMS analysis framework adds a second analytical engine to accompany the life cycle cost analysis in computing project benefits.

The research approach contained the three major elements: (1) A Literature Review and Synthesis, (2) Risk Assessment Methodology development, and (3) proposed AASHTO Guidelines.

# CHAPTER 1 RESEARCH APPROACH

The research team recognized the challenges to state DOTs and other transportation organizations in performing risk assessments of bridges and integrating them into their asset management and bridge management systems. The research effort focused on developing guidelines for a data-driven risk assessment at the bridge and structure level that, at the minimum, considers risks from natural and man-made hazards. The essence of this effort was to ensure that risk assessment is properly understood, identifying needs of DOTs and articulating in the guidance documents what data, tools and methods will address those needs.

The research approach, illustrated in Figure 1, had the three major elements:

1. **Literature Review and Synthesis**. An exploratory phase (Tasks 1 and 2) where the team's current understanding is combined with insights provided by other sources with the resulting assessment of current approaches, practitioner needs and gaps.
2. **Risk Assessment Methodology.** An implementation phase (Task 3) where the team develops an approach that meets practitioner needs in ways that are likely to be implemented in practice and would be suitable for use in a bridge management system.
3. **Proposed AASHTO Guidelines**. The results phase of the effort (Tasks 4, 5 and 6) where the team provides the guidance that practitioners need to implement the methodology.

The final task (Task 7) documents the research conducted with final guidelines that enables state DOTs to make better informed and effective decisions.

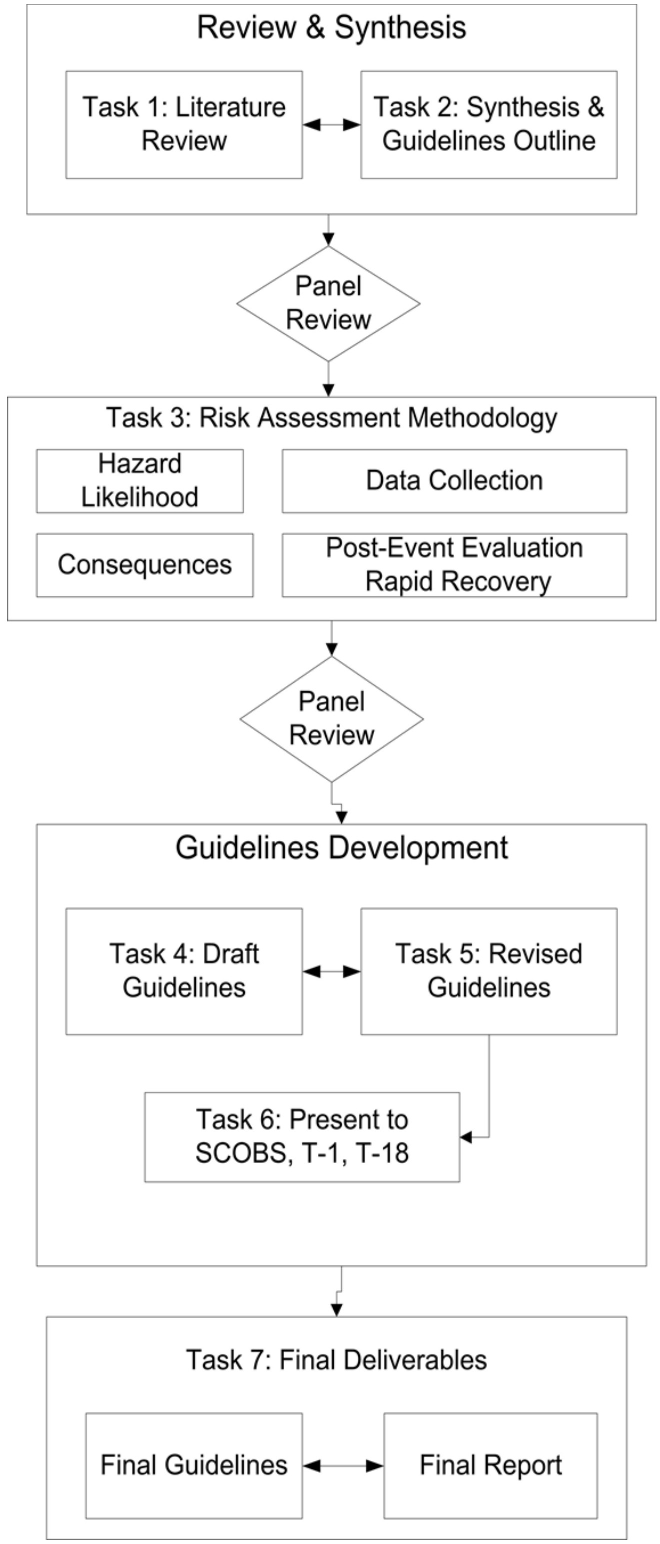


Figure 1 Research Plan

## Chapter 2 LITERATURE REVIEW AND SYNTHESIS

Risk may be understood as the potential for unplanned adverse events to impact one or more transportation facilities in a way that causes unacceptable transportation system performance according to any or all of the agency's performance objectives. In bridge management, the primary concern is disruption of expected or designed service levels, which may cause injuries or property damage, loss of mobility, loss of environmental sustainability, and immediate expenditures or long-term excess costs.

The adverse events which may cause these service disruptions may include natural hazards such as earthquakes, landslides, storm surge, high winds, floods, scour, and wildfires; man-made hazards such as overloads and vehicle or vessel collisions, including vehicles containing flammable cargo; and advanced deterioration related to corrosion, section loss, displacement, or fatigue cracking.

The Moving Ahead for Progress in the 21st Century Act (MAP-21), P.L. 112-141, specifies that asset management shall be risk-based, but does not specify risk performance measures. MAP-21 does specify a set of national performance goals in 23 USC 150(b) including safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays. MAP-21 further promotes decision making which minimizes life cycle costs. Most transportation agencies have similar goals set out in their enabling legislation, mission statements, and/or strategic plans.

Adverse events may affect any or all of the national goal areas listed in 23 USC 150(b). In fact, some of the tools already used for performance modeling in asset management, such as accident analysis, user costs, sustainability performance measures, project cost estimation, and life cycle cost analysis, are highly suitable to assist in estimating the consequences of adverse events. Modern bridge management systems, including the AASHTOWare Bridge Management software (BrM), have multi-objective performance frameworks for project evaluation, priority setting, and resource allocation.

The Synthesis, included in Appendix A, provides a summary of current approaches and gaps in guidance for engineering risk assessment, post-event evaluation for infrastructure assets and rapid recovery strategies. Summary key findings are provided below.

### Key Findings

Information on the likelihood of hazards is well documented on a site-specific basis, but it is fairly difficult to use this type of information to characterize large groups of bridges as is necessary in a bridge management system.

Geographically-referenced data related to adverse event likelihood is easy to access for common natural hazards such as earthquakes, floods, storm surge, and tornadoes. This is highly suitable for use in bridge management systems since it can be used to categorize each and every bridge in an inventory.

There are a number of methodologies associated with assessing transportation assets that incorporate a variety of risk models such as likelihood models, consequence models, delay/detour models and recovery consequence models.

States are currently using different methods and models to evaluate risk. In the case of earthquakes information is relatively well developed in the seismically vulnerable states. The same expertise and capabilities can serve not only in earthquakes, but after other extreme events such as storm surge, wave action, and scour. Databases exist for vehicular impact, floods, fires and other hazards.

Certain natural hazards, specifically landslides, wildfire, sea level rise, extreme temperature, drought, and permafrost thaw, do not have standardized methods in the literature for estimating the likelihood of structural damage or service disruption. Agencies may need to rely on state-specific data sources if they want to incorporate these hazards in bridge management systems.

Methods to quantify collision (e.g. over-height trucks) and overload likelihood are currently not well documented, although Florida DOT does have a model of accident risk due to functional deficiencies, and histograms of truck height and weight. New York and Florida DOTs have developed methods to assess the likelihood of fatigue damage. Both rely on collecting additional data items not generally available in bridge management systems, but both agencies have developed reasonably efficient methods to collect this information.

Florida developed a method to use element level data to compute the likelihood (as a probability) of service disruption due to advanced deterioration. Other states use only condition data as a proxy or classification for this purpose (for example, elements in their worst condition state, or bridges that are structurally deficient due to condition).

Methods to assess safety and mobility consequences of service disruption exist in the user cost models already used in Pontis and models documented in the AASHTO Manual on User and Non-User Benefit Analysis for Highways (“Red Book”). NCHRP Report 590 documents a method to assess consequences using utility theory, which does not require an economic measure for safety, mobility, or environmental impacts.

Clear definitions and terminology are important for correct application of risk management methods. It is necessary to be clear on the definitions of hazards, the cause-and-effect relationship between hazards and service disruption consequences, and the means of quantifying the factors which measure this relationship. Especially important is the definition of “service disruption” as it applies to each evaluated hazard.

Two types of post-event assessments are now being conducted: one of structural integrity and another of network resilience. Structural integrity assessment evaluates the degradation state under an extreme event, whereas the resilience assessment evaluates the system or network’s recovery following extreme events. Structural integrity assessment is well established. Network resilience is a more recent practice. While traffic engineers have been focused on this aspect of transportation networks, it is a relatively new concept to structural engineers.

The post-event assessment of bridges has been enhanced by rapidly developing technologies providing digitized data acquisition, storage and transmission along with structural diagnostics, i.e. monitoring of structures by sensitive instruments measuring temperature, displacement, acceleration, and other significant performance indicators during regular service. A number of remote, in-situ, or portable monitoring/damage detection techniques have become available for use in post-event assessment such as sensors, sonar, ground-breaking radar, satellite imagery and unmanned aerial vehicles. These new capabilities are not fully explored and reflected in systematic guidelines.

A considerable amount of research and practice has been documented on recovery strategies. Thus far this information is very site-specific. Additional work will be required to develop metrics, rules-of-thumb, or other methods to make use of this knowledge on all bridges in an inventory.

Effective decision making requires the use of easily available data, with the use of currently available data being a significant cost saving. State DOTs and other transportation agencies collect and manage large quantities of data. The volume of data can be overwhelming and a fundamental understanding of the system-level behavioral characteristics and the potential impact of the identified conditions on the overall performance of the bridge.

## CHAPTER 3 RISK METHODOLOGY

The research team developed a structure and risk methodology, devoting special attention to the relationship between the needs of risk management and the capabilities of existing bridge management systems, especially the AASHTOWare Bridge Management software. A key requirement for the methodology was that it can be implemented with the aid of the bridge management systems currently used in transportation agencies. This required that it be structured so it fits within the analytical framework of these systems. Figure 2 depicts some of the common ingredients found in bridge management systems, showing where risk assessment can fit in.

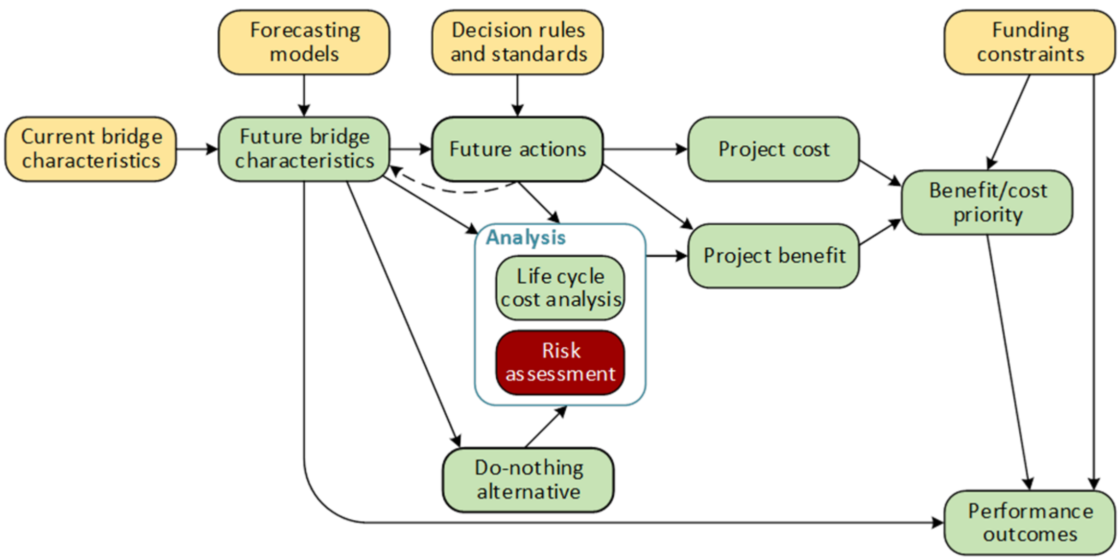


Figure 2: Role of Risk in Bridge Management Systems

For risk assessment is to be built into bridge management systems such as BrM, it needs to fit within the framework of benefit/cost analysis used by those systems to ensure that risk analysis functions as expected alongside life cycle cost analysis in the computation of project benefits. Existing approaches used by some leading agencies in their efforts to support risk-based decision making were reviewed, such as the Florida DOT Project Level Analysis Tool (PLAT), the Minnesota DOT Bridge Replacement and Improvement Management (BRIM) tool, and the New York State DOT Bridge Safety Assurance Program.

Comparing the approaches taken by the agencies and other systems reviewed by the research team, a number of similarities and differences were observed:

- All of the systems rely on the definition of a hazard scenario, which in some cases may be called a disruption or failure scenario. The systems differ in how this scenario is defined: New York considers three scenarios based on extent of structure damage, while Florida and Minnesota only consider events that interfere with normal traffic flow.

- In Florida's system, the scenario definition differs for different hazards. In some cases only the likelihood of an extreme event is estimated, while in other cases the likelihood of service disruption is estimated. This depends on the available data and the nature of the hazard. The other systems tend to apply the same criteria across all hazards, but have less precise definitions.
- Florida and New York explicitly consider the likelihood and consequence of service disruption. Minnesota and the federal sufficiency rating approach do not.
- Florida and New York are also the only two that explicitly consider the likelihood of extreme events.
- All of the systems rely heavily on bridge characteristics that are assessed by inspectors.
- All of the systems apply a multi-objective perspective on consequences: they all consider safety, mobility, and recovery costs in some way, although not always explicitly in the computations.
- The Minnesota and New York systems express risk in categories, as does the AASHTO Assessment feature. Florida and the federal sufficiency rating express risk on a continuous scale. The AASHTO system computes utility on a continuous scale.
- Performance measures used in benefit/cost prioritization in Florida's and AASHTO's systems are expressed on an unbounded scale. The performance measures computed in Minnesota, New York, and the sufficiency rating are on a bounded scale and are not used in benefit/cost analysis.

All existing BMS with the capability of resource allocation and optimization use benefit/cost analysis for setting priorities. As bridge size increases, total project costs tend to increase and the impact of hazards on the network increases as well. It is important for benefits to increase in a manner commensurate with costs in order for benefit/cost analysis to produce consistent results regardless of bridge size.

It was desired that the methodology for risk assessment be able to accommodate a range of preferences and perspectives. Along with being compatible with AASHTOWare BrM and similar bridge management systems that may be developed, the methodology should be able to address a wide variety of hazards and performance criteria so each agency can select the hazards and criteria of most importance.

The methodology should behave in a reasonable way to reflect variations in bridge size, utilization, detour distance, difficulty of incident response and recovery, extreme event probability, and other significant variables affecting risk. To the greatest extent possible, the methodology should approximate stable and measurable engineering and economic concepts, so it can be gradually improved over time with further research.

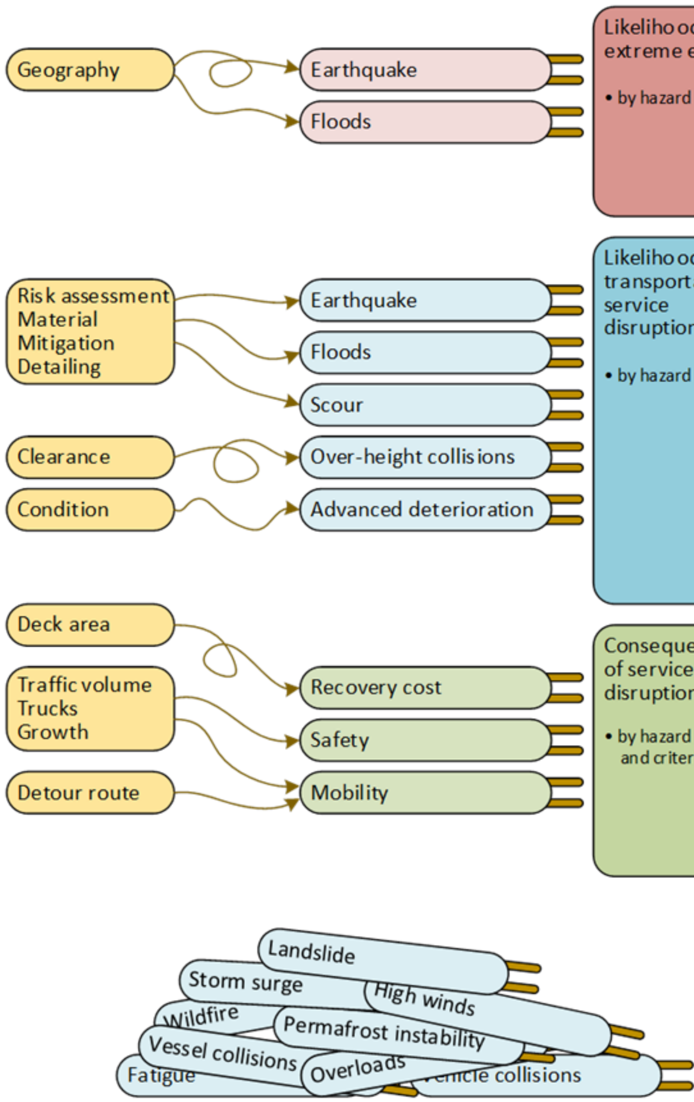


Figure 3. Recommended modular approach to the risk assessment methodology

The recommended methodology developed takes a modular approach, designed to help to organize the various components of the analysis (Figure 3). Each agency has considerable latitude to select the modules relevant to their needs, within the flexibility offered by their bridge management system. Agencies choose which modules to use based on their risk management concerns and data availability. Some of the modules provide multiple computation methods at varying level of data requirements. AASHTOWare Bridge Management, in its 5.2.3 release, is expected to have sufficient capability to support any or all of the methods to be described in the Guidelines.

In the recommended framework, the disutility of an adverse event depends on the nature and magnitude of the hazard, and on the effect on each performance concern. In fact, the analytical methods for estimating likelihood and consequence may differ substantially based on type of hazard and the affected performance criteria. For example, the likelihood of service disruption due to hurricanes depends on the frequency of hurricanes of a specific magnitude at the site, the probability that a hurricane, if it occurs, might lead to bridge damage, and the probability that a bridge, if damaged, might disrupt transportation service. On the other hand, the likelihood of service disruption due to advanced deterioration depends mainly on the type and condition of the structure; the structure is damaged by definition, and the key question is the probability of service disruption. Similarly, the mobility consequence of a service disruption depends on event duration, traffic volume, and detour distance, while the safety consequence depends on traffic volume and the suddenness of the hazard event.

In order to reflect these variations in a reasonable way, the following concepts are defined:

- A hazard scenario, denoted in the equations using the subscript *h*, entails an extreme event of a specific magnitude (if applicable) causing a defined impact on transportation service. For example, a hurricane of at least magnitude 4 that destroys a bridge.
- A performance criterion, denoted using the subscript *c*, represents an agency objective that may be compromised by a hazard scenario. Examples are condition, cost, safety, mobility, and environmental sustainability.

An important decision is the level of disruption that should be incorporated into the threshold for recognition of a hazard scenario. Some of the options are:

- The structure is damaged to at least a defined damage level, typically corresponding to the agency's distinction between routine work orders for repair, and programmed capital projects for mitigation, rehabilitation or replacement.
- Near-term or long-term life cycle costs are increased.
- Transportation service is disrupted, causing a loss of performance in terms of safety or mobility.
- Environmental resources or the property of others are damaged.

Any or all of the above could have a role in defining the criteria for a hazard scenario. For an understandable and consistent analysis, however, it is important to be consistent in definitions across all hazard types. The Guidelines are flexible in allowing agencies to adopt any reasonable set of criteria. However, the service disruption criterion is recommended for primary emphasis, for the following reasons:

- Most of the states having existing risk management capabilities as part of bridge management use this as their criterion (New York is the main exception).
- For most hazard classes, events that cause service disruption also cause structure damage.
- Service disruption events are typically regarded as more severe than damage-only events, and are more likely to be captured in historical records.
- Damage that is significant enough to disrupt service is typically more expensive to repair and more urgent than damage that does not disrupt service.
- Events belonging to some of the hazard types are not typically recognized as risk consequences unless they disrupt service. Examples are extreme temperature, settlement, advanced deterioration, and fatigue.

This report and the proposed Guidelines use the term "service disruption" to characterize a hazard scenario but it should be understood that an agency may adopt different criteria.

The level of detail represented in hazard scenarios can vary based on agency preference. It is likely that most agencies will want to keep the model simple by defining only a small number of scenarios to represent the broader range of possible adverse events. Increasing the number of scenarios increases the development and computational effort, but gives a more precise estimate of outcomes and risk.

If a hazard scenario includes the occurrence of an extreme event, it is desirable to use the event magnitude for which the agency's structures are typically designed. For example, if bridges are typically designed to withstand a 100-year flood, then the 100-year flood is the extreme event magnitude to use, and the extreme event probability is one percent.

Methods for quantifying the likelihood of service disruption vary by hazard type. The literature provides a variety of ways of quantifying event probabilities, or producing scores suitable for utility theory as in NCHRP Report 590. It is becoming common in asset management applications to use a performance concept called "resilience" to describe disruption likelihood on a scale of 0 to 100 in the same way the bridge health index is used for condition. This makes it easier to communicate risk-related trends over time, make comparisons among assets or parts of the inventory, and compute changes or risks to asset value.

In risk analysis, the consequences of transportation service disruption are typically expressed in dollars. Most pavement and bridge management systems have user cost factors for this purpose, the same factors that are also used for analyzing the benefits of functional improvements. AASHTO's Red Book is a well-known reference that can support a standards-based and research-based approach to quantifying these costs. Some agencies prefer to confine the life cycle cost analysis to agency costs, and apply utility theory to represent risk and functional concerns. The literature provides a number of methods for doing this.

Worksheets were developed to assist in estimation of likelihood of service disruption per hazard and consequences of service disruption, recognizing that there are multiple ways of estimating the likelihood and consequences.  The philosophy taken with the worksheet development was to take advantage of all available data, use judgment and only replace data that might be gathered later through improved inspection processes or research.

## Analyzing risk in AASHTOWare Bridge Management

AASHTOWare Bridge Management (BrM) is the first commercially-available BMS that provides a framework for applying risk models. Although it has not been populated with such models as of Release 5.2.2, it has features to allow an agency administrator to input such models without having to access the proprietary source code of the software. Inspectors can enter risk-related assessments of field conditions; analysts can use risk-related formulas to augment the benefit equation in benefit/cost analysis; and engineers can define treatments that mitigate risk. Any other BMS system using benefit/cost analysis can, in principle, be modified to incorporate such models.

BrM provides a generic platform on which risk-related models can be implemented and used in decision-making. The focus of this capability is the Risk Assessment record, part of Bridge Characteristics. If a bridge has a risk-related concern associated with it, the inspector may add a corresponding Assessment record to that bridge in BrM. New Assessment records can be added any time a new assessment is performed. At any given time, the most recent assessment for a given Assessment type is considered to be the current status of the structure. The screen provides workflow information about the assessment and, most importantly, classifies the risk in terms of agency-defined hazard class, likelihood and consequence of service disruption, and affected deck area and traffic volume.

It is important to note that the BrM system and documentation offer no guidance on how hazard class, likelihood, or consequence is to be defined and assessed.

In order to use risk information in the calculation of project benefits, AASHTOWare BrM defines a mathematical formula called a Utility Function, based on the research in NCHRP Report 590. Utility is essentially a unitless composite performance measure that can combine condition, life cycle cost, safety, mobility, and any other performance concern. By convention, utility of 100 is best, and 0 is worst. Deterioration of a bridge may cause its utility to decline over time, and any kind of preservation or risk mitigation work will improve the utility. The improvement in utility is used in computing project benefit.

## CHAPTER 4 PROPOSED GUIDELINES

This section contains the outline for the proposed AASHTO guidelines on assessing risk for bridge management. The complete proposed guidelines are available in Appendix B.

A. Introduction
- Background on risk assessment and management, risk-based asset management, and bridge management systems
- How to use this document

B. Bridge Management System Framework for Risk
- Risk in bridge management systems
- Performance concerns and measures
- Hazards affecting bridges
- Analyzing risk in AASHTOWare Bridge Management
- Glossary

C. Risk Assessment
- Defining hazard scenarios and performance criteria
- Risk Assessment worksheets
    - Estimating likelihood of service disruption scenarios (by hazard class)
    - Estimating the consequences of service disruption (performance concerns)

D. Applications to Risk Management
- Risk management treatments
- Level of service standards for vulnerability/resilience
- Mitigation costs and treatments
- Incorporating risk in asset management

E. Incorporating Risk in Bridge Management Systems
- Established risk assessment tools
- Methodology in AASHTOWare Bridge Management
- Computation of recovery costs

F. Future Research Needs

G. References and Resources

## Chapter 5 AASHTO COMMITTEE FEEDBACK

The research team reached out to relevant AASHTO committees and subcommittees to obtain input and feedback from practitioners at state DOTs during the course of the project. Members of the research team presented the proposed methodology and preliminary Guidelines outline at the AASHTO Subcommittee on Bridges and Structures (SCOBS) T-1 Technical Committee for Bridge Security and Hazards Meeting, held on March 10, 2016. Overall, the committee members liked the direction of the preliminary methodology and guidelines. Questions were asked about how we would quantify the likelihoods of certain hazards and a request was made to include terrorism and other types of intentional damage, e.g. sabotage. Input from the SCOBS T-1 members was incorporated into the draft proposed AASHTO guidelines.

The research team presented the draft proposed guidelines at the AASHTO SCOBS T-1 Technical Committee for Bridge Security and Hazards and the T-18 Technical Committee for Bridge Management, Evaluation, and Rehabilitation during the 2016 Minnesota Bridge Meeting, held on June 27, 2016.

The methodology and proposed guidelines were well received by the members of the two AASHTO technical committees. The committee members found the Task 4 proposed guidelines document very comprehensive and believed that it will be of value to state DOT agencies. There was some concern that there is much to digest and understand and a suggestion was made that including additional examples and an executive summary would be helpful.

These comments have been incorporated into the final version of the methodology and proposed guidelines.

## CHAPTER 6 RECOMMENDATIONS FOR FUTURE RESEARCH

The methodology and proposed guidelines produced in this research project are perfectly positioned to support the state DOTs' focus on risk-based asset management. Based on the feedback from the AASHTO Technical Sub-committees they provide a valuable resource and process for DOTs and transportation agencies as they grapple with agency-wide asset and risk management responsibilities.

Additional research identified during the course of this research project includes:

- Going into more detail on the data needs, requirements and process, including an expansion of the number of examples in the guidelines to be more comprehensive.
- Focusing on the differences between new and existing infrastructure and developing guidance specific to the unique needs and requirements of each in an asset management system.
- Conducting a demonstration project using the methodology with 2-3 states to identify and document how to utilize the methodology and guidelines in a bridge management system, such as AASHTOWare BMS. This would entail going on-site and utilizing actual State DOT inputs and data, working directly with designated state employee(s) assigned to the demonstration project. Clearly defined goals and measurement criteria would be developed to support later evaluation of the methodology and guidelines benefits and overall usability.
- Documenting the operational incident response processes that states use when dealing with unplanned events, and incorporating the various patterns of response into the methodology and guidelines. A survey of State DOTs is an option to be considered to collect information in a cost-effective manner from state DOTs. Conducting a group session with state DOT representatives to share approaches and experiences, ideally during an AASHTO or TRB conference where agency personnel have gathered, is another option. The research team has used this approach successfully to gather information about current practices and challenges as part of previous TRB research projects.
- There is no comprehensive reference, similar to these Guidelines, for identifying appropriate risk mitigation treatments, establishing warrant criteria, and for estimating treatment cost and effectiveness. Development of such a document would be a logical next step. The work would likely require a survey of the states (possibly combined with the survey of incident response processes described above) and an in-depth examination of methods and project histories from a selection of states.
- For many common hazards, there is considerable anecdotal evidence of damage and service disruptions from adverse events, but this information is in fragmented sources that have not been brought together for the purpose of a bridge management risk assessment. A national-scale effort could compile this information and provide a stronger risk allocation calculation than any individual state could accomplish by itself. The work described in Stein and Sedmera (2006) for scour is a good example.
- While many agencies are likely to implement these guidelines within AASHTOWare Bridge Management, there are certainly many other potential applications of the risk analysis for more

specialized purposes such as site-specific studies, policy analysis, and development of mitigation programs. There may be enough of these applications to justify the development of a stand-alone spreadsheet application that implements these Guidelines. The advantage of a spreadsheet application for this purpose is that it could readily be modified by agencies and consultants to match the special needs of each agency.

- The quantification of environmental sustainability consequences in these Guidelines can be improved by considering carbon dioxide emissions and by modeling the effects of hazard scenarios on water, agricultural, recreational, and cultural resources.
- Some initial work has been done on the assessment of bridge structural characteristics in relation to damage and disruption due to storm surge and tsunami (Sobanjo and Thompson 2013), but this could be improved by the systematic examination of storms from multiple states. In addition, there has been recent work on geographically-referenced forecasting of sea level rise, which needs to be associated with bridge and site characteristics to improve the estimates of likelihood of service disruption.
- There is substantial room for improvement in the ability to quantify the relationship between scour and flood characteristics and the likelihood of service disruption. The methods described in this guide depend primarily on NBI data and might be improved by means of a field assessment of the most significant variables in the structural response.
- Over-height truck collisions are quite common and can cause a wide range of disruptions depending on the characteristics of the impacted bridge. There is potential for research to develop a field assessment of bridge characteristics, and corresponding disruption likelihood and consequence models, that estimate the duration and severity of such collision events.
- Related to the previous need, there is a need for research on the effectiveness of mitigation strategies related to overload and over-height hazards. These measures might include enforcement strategies, sensors, portal frames, and signage. These results should be integrated with the field assessment so their use can influence the estimates of disruption likelihood and consequences.
- Florida DOT research (Sobanjo and Thompson 2013) found that advanced deterioration was, by far, the biggest contributor to bridge risk in its inventory. The research developed a lognormal model to aid in forecasting this hazard. Given its importance, further research would be justified to analyze other state inventories and to relate the likelihood of service disruption to the new data available under the 2013 AASHTO Guide for Bridge Element Inspection.
- Individual agencies may wish to research the extreme event likelihood of natural hazards most affecting them. In some cases, such as wildfires, this may involve creating new geographic resources (fuel availability maps) that do not yet exist in the state. In other cases, it may involve cleanup and mining of existing geographic databases. Flood and landslide databases, in particular, are subject to changing conditions where frequent updates can improve data quality.
- Agencies having bridges over significant navigable waters may want to research the influence of vessel and waterway characteristics on the likelihood and consequences of vessel collisions. The available information is fragmented and would require some further manipulation and data collection to maximize its usefulness in a BMS risk assessment.

Although not specifically related to this project, TRB has recently embarked upon a major effort to increase the implementation its research products, tools, documents and materials. There are a number of future research efforts that would support and reinforce the implementation of the guidelines in state DOTs such as.

- Providing additional support tools and guidance for practitioners to implement the methodology such as an easy to use User's Guide, extensive examples of usage and an executive summary presentation in template format that agency staff can use to gain "buy-in" from their senior management to support the bridge management program as well as the agencies asset management program

- Developing Case Studies of the demonstrate usage of the guidelines and methodology in state DOTs. Outreach to State DOTs would be required as part of the effort to produce the case studies.

- Conducting outreach to AASHTO and TRB committees at various national, regional and state meetings to support the implementation of the guidelines, such as presenting at sessions and conducting webinars.

## APPENDIX

A. Literature Review and Synthesis

B. Proposed Guidelines

# Appendix A Literature Review

# Contents

## A. Overview and Key Findings

Risk may be understood as the potential for unplanned adverse events to impact one or more transportation facilities in a way that causes unacceptable transportation system performance according to any or all of the agency's performance objectives. In bridge management, the primary concern is disruption of expected or designed service levels, which may cause injuries or property damage, loss of mobility, and immediate expenditures or long-term excess costs.

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This Synthesis, Task 2 of NCHRP 20-07 Task 378, provides a summary of current approaches and gaps in guidance for engineering risk assessment, post-event evaluation for infrastructure assets and rapid recovery strategies.

### Key Findings

- Information on the likelihood of hazards is well documented on a site-specific basis, but it is fairly difficult to use this type of information to characterize large groups of bridges as is necessary in a bridge management system.

- Geographically-referenced data related to adverse event likelihood is easy to access for common natural hazards such as earthquakes, floods, storm surge, and tornadoes. This is highly suitable for use in bridge management systems since it can be used to categorize each and every bridge in an inventory.

- There are a number of methodologies associated with assessing transportation assets that incorporate a variety of risk models such as likelihood models, consequence models, delay/detour models and recovery consequence models.

- States are currently using different methods and models to evaluate risk. In the case of earthquakes information is relatively well developed in the seismically vulnerable states. The same expertise and capabilities can serve not only in earthquakes, but after other extreme events such as storm surge, wave action, and scour. Databases exist for vehicular impact, floods, fires and other hazards.

- Certain natural hazards, specifically landslides, wildfire, sea level rise, extreme temperature, drought, and permafrost thaw, do not have standardized methods in the literature for estimating the likelihood of structural damage or service disruption. Agencies may need to rely on state-specific data sources if they want to incorporate these hazards in bridge management systems.

- Methods to quantify collision (e.g. over-height trucks) and overload likelihood are currently not well documented, although Florida DOT does have a model of accident risk due to functional deficiencies, and histograms of truck height and weight. New York and Florida DOTs have developed methods to assess the likelihood of fatigue damage. Both rely on collecting additional data items not generally available in bridge management systems, but both agencies have developed reasonably efficient methods to collect this information.

- Florida developed a method to use element level data to compute the likelihood (as a probability) of service disruption due to advanced deterioration. Other states use on condition data for this purpose (for example, elements in their worst condition state, or bridges that are structurally deficient due to condition).

- Methods to assess safety and mobility consequences of service disruption exist in the user cost models already used in Pontis and models documented in the AASHTO Manual on User and Non-User Benefit Analysis for Highways ("Red Book"). NCHRP Report 590 documents a method to assess consequences using utility theory, which does not require an economic measure for safety, mobility, or environmental impacts.

- Clear definitions and terminology are important for correct application of risk management methods. It is necessary to be clear on the definitions of hazards, the cause-and-effect relationship between hazards and service disruption consequences, and the means of quantifying the factors which measure this relationship. Especially important is the definition of "service disruption" as it applies to each evaluated hazard.

- Two types of post-event assessments are now being conducted: one of structural integrity and another of network resilience. Structural integrity assessment evaluates the degradation state under an extreme event, whereas the resilience assessment evaluates the system or network's recovery following extreme events. Structural integrity assessment is well established. Network resilience is a more recent practice. While traffic engineers have been focused on this aspect of transportation networks, it is a relatively new concept to structural engineers.

- The post-event assessment of bridges has been enhanced by rapidly developing technologies providing digitized data acquisition, storage and transmission along with structural diagnostics, i.e. monitoring of structures by sensitive instruments measuring temperature, displacement, acceleration, and other significant performance indicators during regular service. A number of remote, in-situ, or portable monitoring/damage detection techniques have become available for use in post-event assessment such as sensors, sonar, ground-breaking radar, satellite imagery and unmanned aerial vehicles. These new capabilities are not fully explored and reflected in systematic guidelines.

- A considerable amount of research and practice has been documented on recovery strategies. Thus far this information is very site-specific. Additional work will be required to develop metrics, rules-of-thumb, or other methods to make use of this knowledge on all bridges in an inventory.

- Effective decision making requires the use of easily available data, with the use of currently available data being a significant cost saving. State DOTs and other transportation agencies collect and manage large quantities of data. The volume of data can be overwhelming and a fundamental understanding of the system-level behavioral characteristics and the potential impact of the identified conditions on the overall performance of the bridge superstructures may be lacking.

## B. Existing Practices to Assess Risk from Natural and Man-Made Hazards

### Overview of Risk

Risk may be understood as the potential for unplanned adverse events to impact one or more transportation facilities in a way that causes unacceptable transportation system performance according to any or all of the agency's performance objectives. In bridge management, the primary concern is disruption of expected or designed service levels, which may cause:

- An immediate need for expenditures to clear and repair damage, and/or restore the intended level of service;
- Long-term excess costs to keep a bridge in service at an acceptable level, including the need to repeatedly perform unplanned repairs to a bridge because of unmitigated hazards;
- Injuries or property damage related to bridge damage or unacceptable performance of safety features;
- Loss of mobility related to obstruction of the traveled way, or due to concerns about the ability of a bridge to carry the intended vehicles;
- Harm to the environment from unintended deposition of chemicals or debris in natural areas.

In general, risk is the product of likelihood and consequence. This product might be an economic quantity if a social cost framework is chosen, or it might be a utility value or a risk classification.

There have been a number of recent NCHRP reports that provide overviews and case studies describing how state DOTs are utilizing risk assessment and risk management techniques in their planning, operations, and program/project management. NCHRP 20-24 (74) Executive Strategies for Risk Management by State DOTs[1] (2011) conducted a review of transportation, planning, and business management to identify risk management practices and emerging methods related

[1] D'Ignazio, J., Hallowell, M., & Molenaar, K. (2011). Executive Strategies for Risk Management by State Departments of Transportation. Transportation Research Board, Washington DC.

to internal operations and program and project delivery. The study looked at DOT risk management practices at the enterprise, program, and project levels, but focused more on enterprise risk management. The project final report includes an overview of general risk management process and techniques as they apply to DOTs.

NCHRP Report 706 Uses of Risk Management and Data Management to Support Target-Setting for Performance-Based Resource Allocation by Transportation Agencies[2] (2011) focused on risk management to support funding decisions and prioritization of projects. The report includes case studies of DOT bridge risk assessment process from Georgia, Minnesota, Washington State and others plus a summary of risk management implementation considerations based on the common themes found in the case studies and recommended next steps.

A literature review of documented studies and articles related to risk and the analysis of hazards on bridges was included in Development of Risk Models for Florida's Bridge Management System: Final Report[3] (2013).

### Existing Risk Models

There are a number of methodologies associated with assessing transportation assets that incorporate a variety of risk models such as likelihood models, consequence models, delay/detour models and recovery consequence models. Likelihood models relate historical adverse event frequency, deterioration, and resilience to the probability of service disruption. Consequence models monetize mobility, safety, and recovery impacts. Delays and detour models monetize the impact based on the time value of delay and the vehicle per-mile operating costs.

State DOTs have applied risk models to support a range of mission-related activities. The Georgia Department of Transportation (GDOT) has developed an approach for incorporating risk considerations into the prioritization of pavement and bridge preservation that considers both the current condition and the risk associated with its failure. A Minnesota Department of Transportation (Mn/DOT) process applies risk management to programming of bridge rehabilitation and replacement projects. This process was developed at the request of the Mn/DOT Commissioner early in 2008, and was part of a larger effort to integrate risk assessment and management into the agency. Washington State DOT planners, bridge engineers, and materials engineers have been working together to identify ways to evaluate bridge projects by weighing the risks of failure and impacts against other potential projects. The California Department of Transportation bridge retrofitting prioritization process was based on an algorithm that considered a weighted combination of hazards, impacts, and vulnerability of bridges.

The Florida DOT, in Development of Risk Models for Florida's Bridge Management System: Final Report[4] (2013), conducted an assessment of hazards in terms of their likelihoods (expressed as a probability in percentages), and the consequences of the hazard event to the structure in terms of a choice of agency actions with estimated or expected value of cost and in

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[2] American Association of State Highway, Transportation Officials, National Cooperative Highway Research Program, & Cambridge Systematics. (2011). Uses of Risk Management and Data Management to Support Target-setting for Performance-based Resource Allocation by Transportation Agencies (Vol. 706). Transportation Research Board.

[3] Development of Risk Models for Florida's Bridge Management System: Final Report. Sobanjo, John O., and Paul D. Thompson. Florida Department of Transportation Contract BDK83 977-11, 2013.

[4] Op. Cit. Sobanjo et. al. 2013.

terms of the impact on the public and the environment in the form of social costs - a sum of agency, user, and non-user costs. Hazards included in the Florida Risk Model study included weather related hazards such as hurricanes, wildfires, tornadoes and flooding, collisions and overloads, and infrastructure aging events such as fatigue and advanced bridge deterioration.

Risk Based Bridge Planning in Minnesota[5] (Thompson, Rogers, and Thomas, 2012) contains another approach that is less quantitative than that used in the Florida DOT.[6]

NCHRP Report 590: Multi-Objective Optimization for Bridge Management Systems[7] (2007) contains a more rigorous non-economic approach based on multi-attribute utility theory. This approach was the basis for the development of the AASHTOWare BrM software.

A draft framework for geotechnical asset management developed for Alaska DOT based on earlier work in bridge management systems, is focused on risk assessment and management, and is relevant to the current effort because it has been updated based on MAP-21 concepts.

### Addressing Hazards

The adverse events which may cause service disruptions include natural hazards such as earthquakes, landslides, storm surge, high winds, floods, scour, and wildfires; man-made hazards such as overloads and vehicle or vessel collisions, including vehicles containing flammable cargo; and advanced deterioration related to corrosion, section loss, displacement, or fatigue cracking. The following table provides a summary of the impact on a bridge of each hazard, based on information found during the course of the research.

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[5] Risk Based Bridge Planning in Minnesota. Thompson, Paul D., Hal Rogers, and Dustin Thomas. Proceedings of the Sixth International Conference on Bridge Maintenance, Safety, and Management, Como, Italy. 2012a

[6] See Thompson, Paul D., Hal Rogers, and Dustin Thomas. Risk Based Bridge Planning in Minnesota: Proceedings of the Sixth International Conference on Bridge Maintenance, Safety, and Management, Como, Italy. 2012.

[7] Patidar, V. (2007). Multi-objective optimization for bridge management systems (Vol. 67). Transportation Research Board.

## Table 1: Hazard Impact on Bridges

| Hazard | Impact | | | Source |
|---|---|---|---|---|
| | **Superstructure** | **Substructure** | **Operations, Maintenance & Safety** | |
| Earthquakes | Damage to connection between superstructure and substructure; shifting of spans causes additional damage to other parts of the bridge, including abutments, bent caps, and girders | Damage due to ground motion and liquefaction | Safety risks | NCHRP Report 472 Comprehensive Specifications for the Seismic Design of Bridges, FHWA Seismic Retrofit Manual, AASHTO Guide Specifications for LRFD Seismic Bridge Design. |
| Landslides | Damage from movement of substructure; Soil & landslide related material on decks | Weaken or move supporting substructure | Safety risks | Bridge Engineering Handbook: Construction and Maintenance. CRC press, 2014. Chen, Wai-Fah, and Lian Duan, eds. |
| Storm Surge | Damage to connection between superstructure and substructure; shifting of spans causes additional damage to other parts of the bridge, including abutments, bent caps, and girders | Debris impact damage | Safety risks | Douglass et al., 2008; Padgett et al., 2008; Padgett et al., 2009 AASHTO Guide Specs for Bridges Vulnerable to Coast Storms |
| Sea Level Rise | Increases baseline water level affecting scour calculations | Increasing the baseline water level affects scour calculations | Decreased clearance | Froehlich, 2003 |
| High Winds | Additional horizontal loading; strong winds create more powerful waves, which can stress superstructure | High flow velocities , bridge scour | Service closure | Easterling, 2002 |
| Floods | Lateral forces on girders, parapets, and railings; debris on decks | Local scour depth changes | Debris and physical damage limitations | HEC-18 (FHWA, 2012a) |
| Scour | Damage or collapse due to structural damage | Erosion to bridge supports | Safety and mobility impacts | HEC-18 (FHWA, 2012a) |
| Wildfire | Debris flow - drag, buoyancy, lateral impact or burial - can result in displacement, | Debris flow damage to bridge abutments | subsequent debris-flow occurrence | Cannon and DeGraff, 2009 |

| | | | | |
|---|---|---|---|---|
| | lifting off foundations, or structural damage from debris flow | | | |
| Extreme Temperature | Thermal Expansion | Thermal Expansion | Unsafe temperature-related conditions | Bridges are designed to withstand a range of temperature change of about 120°F, from -20°F to 100°F (Zimmerman, 1996). |
| Drought | Reduction in ground water can lead to land subsidence | Reduction in ground water can lead to land subsidence | No documented relationship | USGS California Water Science Center |
| Permafrost Thaw | Collapse from substructure shifting | shifting of bridge substructures including pilings, abutments, or approaches | Higher maintenance cost | National Snow & Ice Center; UNEP, 2012 |
| Overloads | Damage or collapse, accelerate deterioration of decks | Damage | Higher maintenance cost | AASHTO LRFD Bridge Design Specifications |
| Vehicle/vessel collisions | Damage or collapse due to collision with bridge span or from substructure damage | Damage from collision with pilings or abutments | No documented relationship | AASHTO Bridge Specifications and Vessel Collision guidance |
| Corrosion<br>Section loss<br>Displacement<br>Fatigue cracking | Damage resulting in reduced service life or collapse | Damage or increased stress | Safety and mobility impacts; higher maintenance cost | AASHTO (2011). The manual for bridge evaluation. 2nd ed. |

NCHRP Synthesis 20-05/Topic 46-11 Post-Extreme Event Damage Assessment and Response for Highway Bridges[8] surveyed state bridge and hydraulic engineers to determine the likelihood of different events occurring in each state, including natural and man-made hazards. The Table below provides a summary of the survey findings. Collision was ranked first and considered as an event with a high likelihood by 34% of the responding engineers. Scour-related failures (with 20% considering high likelihood), wind-related failures (with 18% considering high likelihood), and flood/debris flow (with 16% considering high likelihood) followed. Follow-up interviews found that the high ranking of wind events was based on secondary effects of the high winds (e.g. falling of debris, power lines, signs, etc.) which hinders the serviceability and performance of bridges and not due to any direct impact on the structure of the bridges. Flood/debris flow and scour were ranked as the events with highest likelihood for hydraulic engineers.

**Table 2: Hazards Ranked by Expected likelihood (Highest to Lowest)**

| Bridge Engineers | Hydraulic Engineers |
|---|---|
| Collision | Flood/debris flow |
| Scour | Scour |
| Wind | Storm surge/waves |
| Flood/Debris flow | |
| Landslide | |
| Fire | |
| Storm surge/waves | |
| Earthquake | |
| Blast | |
| Liquefaction | |

The Synthesis 46-11 authors addressed the differences in results between hydraulic and bridge engineers.

> *Reviewing the results of the surveys reveals that in contrast with the current statistics that underline hydraulic reasons (such as flood, scour, and debris accumulation) as the major reason for bridge failures, the state Bridge Engineers have identified collision as the primary reason of failures or disruption in service for the bridges. This discrepancy can mainly be attributed to the fact that in most of the state DOTs, the issues related to hydraulic events are first referred to hydraulic engineers and as such don't necessarily come up as a main cause of failure for all the bridge engineers.*

The Florida DOT research on hazards conducted as part of the Florida Risk Model study cited previously contains a good survey for each type of hazard included in that research - weather related hazards such as hurricanes, wildfires, tornadoes and flooding, accidents such as collisions, and infrastructure aging events such as fatigue and advanced bridge deterioration.

In the case of earthquakes information is relatively well developed in the seismically vulnerable states. The same expertise and capabilities can serve not only in earthquakes, but after other extreme events such as storm surge, wave action, and scour. Databases do exist for vehicular impact, floods, fires and other hazards.

[8] Under development. Preliminary draft of Final Report was obtained from TRB by research team.

Specific hazard-related research includes NCHRP Report 761: Reference Guide for Applying Risk and Reliability-Based Approaches for Bridge Scour Prediction[9] (2013) which focused on developing a risk-based methodology for calculating bridge pier, abutment, and contraction scour at waterway crossings that can be linked to Load and Resistance Factor Design (LRFD) approaches in use by structural and geotechnical engineers. NCHRP 12-85 Highway Bridge Fire Hazard Assessment[10] (2013) addressed fire damage to highway bridges and included guideline specifications for the evaluation of highway bridge structures following fire events.

## C. Existing Methods for Post-Event Evaluation of Damage and Rapid Recovery

The research statement for NCHRP Synthesis 20-05/Topic 46-11 Post-Extreme Event Damage Assessment and Response for Highway Bridges succinctly summarized the current state of post-event assessment for highway bridges. The Synthesis found that two types of assessment are now being conducted: one of structural integrity and another of network resilience.

Post-earthquake rapid and detailed structural assessments of bridges and other structures have been developed and refined after every such event over the last several decades. Visual field inspections have been most informative and have been systematized in a number of manuals. Typically, a first post-event inspection report is produced soon after the event to make determinations on the integrity of the affected structures and their load-carrying capacity.

The assessment of bridges has been enhanced by rapidly developing technologies providing digitized data acquisition, storage and transmission along with structural diagnostics, i.e. monitoring of structures by sensitive instruments measuring temperature, displacement, acceleration, and other significant performance indicators during regular service. A number of remote, in-situ, or portable monitoring/damage detection techniques have become available for use in post-event assessment such as sensors, sonar, ground-breaking radar, satellite imagery and unmanned aerial vehicles. These new capabilities are not fully explored and reflected in systematic guidelines.

### Overview of Assessment Methods

At the federal level, the Federal Highway Administration has published a Bridge Inspector's Reference Manual[11] (2012). The NY State DOT Bridge Safety Assurance Manuals[12] (2013) may be one of the most complete set of guides on field risk assessment for bridges.

Hazard-specific guidance and methods have been developed for post-event assessments of bridges. NYDOT has developed Post-Earthquake Bridge Inspection Guidelines[13] (2010).

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[9] NCHRP Report 761: Reference Guide for Applying Risk and Reliability-Based Approaches for Bridge Scour Prediction, Transportation Research Board of the National Academies, 2013

[10] NCHRP 12-85 Highway Bridge Fire Hazard Assessment, Transportation Research Board of the National Academies, 2013

[11] Ryan, T. W., Hartle, R. A., Mann, J. E., & Danovich, L. J. (2012). Bridge inspector's reference manual. Report No. FHWA NHI, 03-001.

[12] Bridge Safety Assurance Manuals: Hydraulic Steel Details, Overload Collision, Concrete Details and Seismic, New York State Department of Transportation, 2013

[13] O'Connor, J. S. (2010). Post-Earthquake Bridge Inspection Guidelines (No. C-06-14), MCEER/University at Buffalo SUNY.

CalTrans and the California Emergency Management Agency have developed the California Safety Assessment Program (SAP) – an evaluation approach for bridges and other infrastructure after a disaster. Tools and procedures to improve the post-event prioritization of bridge inspections developed by WSDOT[14] in 2005.

As a result of the Minnesota I-35W bridge collapse and subsequent investigation, the FHWA issued Gusset Plate Evaluation Guidance – Part A and Part B (2009) to provide guidelines to bridge owners in meeting the requirements of the FHWA Technical Advisory T 5140.29 Load-carrying Capacity Considerations of Gusset Plates in Non-load-path Redundant Steel Truss Bridges (issued on January 15, 2008).

NCHRP Report 782 Proposed Guideline for Reliability-Based Bridge Inspection Practices[15] (2014) describes a methodology to develop a risk-based approach for determining the bridge inspection interval according to the requirements in the MAP-21 legislation.

### Overview of Assessment Techniques and Technology

Assessment of damaged infrastructure should be conducted as quickly as possible. Traditional disaster assessment practices involve both detailed and rapid ground surveys, which may be difficult to do. It may be dangerous for an assessment team to be in the area after a natural disaster. If the event covers a large area, there may be not be enough survey teams to cover the entire affected area. Remote sensing technologies are being used to detect and locate damage to overcome these limitations, since data can be obtained from structures without making physical contact. In addition, post-disaster data over a large area can be obtained more quickly compared to in-field surveying.

The 46-11 Synthesis survey and follow-up interviews of structural and hydraulic engineers found that 100% of the structural engineers who responded count on visual inspection, either cursory or more detailed at arm-reach inspection, as the first approach to examine the damage to bridges. In many cases the final decisions would be made based on the results of visual inspection, while in some other cases, they would resort to other methods for a more in-depth detection of damage. Hand held non-destructive testing techniques (NDT) (e.g. magnetic particle testing, dye penetrant testing, ultra-sonic testing, hammer sounding, chain drag and rebar scanner) hold the second rank after visual inspection. Similar to state bridge engineers, visual inspection was considered as the first and major approach for damage detection for hydraulic engineers with 100% of responding states using it, followed by portable sonar surveys and manned/unmanned sonar surveys ranking as second and third, respectively.

More advanced technologies have been developed or are under development with potential for emergency damage assessment. The table below provides an overview of assessment techniques and technologies based on Synthesis 46-11.

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[14] See Information Tools to Improve Post-Earthquake Prioritization of WSDOT Bridge Inspections, Washington State Transportation Center, 2005.

[15] NCHRP Report 782 Proposed Guideline for Reliability-Based Bridge Inspection Practices, Transportation Research Board of the National Academies, 2014

## Table 3: Assessment Techniques and Technologies

| Technique | Pros | Cons | Limitations |
|---|---|---|---|
| Visual Inspection | immediate results, inexpensiveness, minimum preparation or special skills required | variations in state practices and inspector use of inspection methods | Only visible elements & defects; Cannot access hard to reach sites |
| Sonar | provides continuous data during and right after high floods, | Low depth tolerance, installation depth and resolution distance between the head and interface affects reading | Instrument location may be limited |
| Photogrammetry | Provides visual recording, high accuracy, low cost | Need to be calibrated | Camera positioning and placement of target points |
| Inclinometer/Tiltmeter | Invulnerability to damage caused by floating debris, reading is not affected by the turbidity or accumulation of debris, longitudinal and transverse inclination can be read, and easy to install. | Difficult to set the critical tilt angle | Cannot quantify the scour depth |
| Ground penetrating radar | Generates tomography of bridge deck | Quality depends on data sampling, longitudinal resolution, and distance between successive scan lanes | Limited application |
| Accelerometers | Low cost, simple installation | Maintenance, numerous false errors, and availability of continuous power supply | Requires placement away from cracks, and suitability for low to medium frequencies due to noise |
| Float-out and tethered buried switches | Low cost, easy to install | Maintenance issues, numerous false alarms | only provide Local scour depth information, only triggered when in the horizontal position |
| Sliding Magnetic collars | Continuous monitoring of the streambed can be obtained during and after major flood event | Can become buried, conduit required for manual reading is vulnerable to ice and debris impact | Can only provide maximum scour depth |
| Satellite Imagery - optical satellites and synthetic aperture radar (SAR) | Provide quick damage detection and change evaluation of area's surface. | Severe weather conditions, like heavy rainfall, can affect the quality, sensitive to surface variations | Efficiency of optical imagery acquisition process is often diminished due to communication interruptions |
| Light Detection and Ranging (LiDAR) | Economical in terms of speed, accuracy, and | Road conditions and GPS outages affected | Dependent on GPS signal |

| | | | |
|---|---|---|---|
| | density | overall efficiency | |
| Unmanned Aerial Vehicles (UAVs) | Low-cost, flexible and ease of operation; efficient tool in delivering high-resolution images after events | Only recently been implemented; weather conditions affect performance; still an active area of research | Insurance issues, regulatory issues, and lack of safe communication frequencies |

Synthesis 46-11 concludes that two types of assessment are now being conducted: one of structural integrity and another of network resilience. Structural integrity assessment evaluates the degradation state under an extreme event, whereas the resilience assessment goes beyond this point and evaluates the system's or network's recovery following extreme events. Structural integrity assessment is well established. Network resilience is a more recent practice. While traffic engineers have been focused on this aspect of transportation networks, it is a relatively new concept to structural engineers.

Synthesis 46-11 discusses resilience in terms of absorptive, adaptive and restorative capacity.

> *The absorptive capacity of a system is its ability to withstand a given level of stress without loss of function. As an example, strengthening the bridge piers with steel jackets in seismic areas increases their capacity to absorb ground vibrations. The adaptive capacity of the system shows the extent to which alternative components exist to satisfy performance requirements in the event of losses in some components of the network. For instance, implementing redundancy for the critical roadways and bridges in a transportation network, increases the likelihood of having functional detours with acceptable lengths in case of failure of any of the links. The restorative capacity is the capability of the system to meet priorities and achieve goals in a timely manner so that recovery from a disruptive event can be accomplished as quickly as possible with the minimum cost. The restorative capacity could be improved by a number of strategies such as having rapid damage assessment techniques that would help identify the source and extent of the structural problems, implementing emergency response plans that would define the responsibilities of different involved parties in the most chaotic times after the extreme event, holding regular training sessions for the agency personnel to be prepared for the aftermath of extreme events ad be familiar with their roles, plan for the available repair and replacement resources, and many other strategies that could be considered to increase the speed of the recovery with the optimized resources.*

### Post-Event Strategies for Recovery

Planning of post-event recovery strategies and their effective implementation enhances the resilience of a structure by reducing recovery time which then supports the resilience of the network.

NCHRP Report 753: A Pre-Event Recovery Planning Guide for Transportation[16] (2013) included approaches and resources for post-event assessment and rapid recovery. The second Strategic Highway Research Program (SHRP 2) S2-R04-RR-1: Innovative Bridge Designs for Rapid Renewal[17] (2012) documented standardized approaches to designing and constructing

[16] NCHRP Report 753: A Pre-Event Recovery Planning Guide for Transportation, Transportation Research Board of the National Academies, 2013

[17] Strategic Highway Research Program (SHRP 2) S2-R04-RR-1: Innovative Bridge Designs for Rapid Renewal, Transportation Research Board of the National Academies, 2012

complete bridge systems for rapid renewal. It developed an "Innovative Designs for Rapid Renewal Toolkit" that describes standardized approaches to designing and constructing complete bridge systems for rapid renewals. It also described a case study on the accelerated bridge construction techniques used in the I-84 bridge project in New York.

Accelerated Bridge Construction (ABC) is bridge construction that uses innovative planning, design, materials, and construction methods in a safe and cost-effective manner to reduce the onsite construction time that occurs when building new bridges or replacing and rehabilitating existing bridges. The Federal Highway Administration's Accelerated Bridge Construction website contains information on project planning, geotechnical such as foundations and wall elements, and structural solutions such as prefabricated elements/systems and structural placement methods.

Rapid Bridge Replacement: Processes, Techniques and Needs for Improvement[18] (2006) provided research results from a project designed to identify rapid bridge replacement processes, techniques, and needs for improvements. The authors analyzed three examples of bridge replacements following extreme events as part of the research. Processes and Techniques for Rapid Bridge Replacement After Extreme Events[19] (2007) provided the results of a pooled-fund research project to identify rapid bridge replacement processes and techniques after extreme events. Repair methods included methods for demolition of unsound concrete, brick or steel and details for the repair of concrete, steel reinforcement, and embedded elements.

Rapid Bridge Deck Replacement Construction Techniques: State of the Practice[20] (2010) assessed the state-of-the practice for Rapid Bridge Deck Replacement (RBDR), the method of replacing a bridge deck through an accelerated construction schedule and use of alternative deck systems. A survey of all State Highway Agencies and some tollway authorities within the United States found that of the 24 responding agencies, 83% had experience with precast decks and 63% have experience with CIP decks, while 58% have employed overlays on at least one project.

Bridge replacement projects using prefabricated or modular elements minimized the weather impact on production and delivery, which in turn shortened the reconstruction process. The state of California Department of Transportation (CalTrans) has developed an emergency highway replacement process using pre-cast concrete panels to quickly repair damaged roadbeds or bridge decking. CalTrans found that using this method is considerably simpler than the standard method. The panels install quickly –"We can close the lane, install the panel and reopen to traffic all within three hours," according to CalTrans' Debbie Wong[21] - thereby minimizing closures. They can also be removed and reused somewhere else. Additionally, they can be installed in any weather and last a long time, estimated at 50 years.

[18] Bai, Y., & Burkett, W. R. (2006). Rapid bridge replacement: Processes, techniques, and needs for improvements. Journal of construction engineering and management, 132(11), 1139-1147.
[19] Bai, Y., & Hoon Kim, S. (2007). Processes and techniques for rapid bridge replacement after extreme events. Transportation Research Record: Journal of the Transportation Research Board, (1991), 54-61.
[20] Flowers, J., Zech, W., & Abbas, H. (2010). Rapid bridge deck replacement construction techniques: State of the practice. Transportation Research Record: Journal of the Transportation Research Board, (2152), 39-48.
[21] Markham, K. "A Concrete Solution to Freeway Repair: D7 Road Tests an Innovative Precast Panel Strategy", Inside Seven, CalTrans District Seven Newsletter, 04/2013.

The state of Vermont maintains a stock of temporary bridges to use when needed and has polices in place that establish limits on the duration of use to ensure that the temporary bridges do not become permanent bridges.

Accelerated work schedules can be used to complete recovery projects in shorter periods of time. This approach was used in the reconstruction of the I-40 and I-95 bridges. According to research studies, accelerated construction at a reasonable cost and with a safe project site environment requires coordination and cooperation between all project participants. Planning in advance can help establish the relationships and communication necessary to achieve the required levels of coordination and cooperation.

Establishing relationships ahead of time – both formal and informal relationships established with contractors and with suppliers – speeds up work to be done to repair the damage structure thus reducing the time to recovery. Pre-contracting – contracts issued prior to an event often called pre-event, pre-positioned or standby contracts – can help expedite recovery. In addition to enhancing resilience, pre-event contracts help avoid the "just in time" emergency contract process. By avoiding the rush during the emergency, the agency can deliberately develop the scope of work, more extensively advertise the opportunity and have more time for the selection process and issuance of the contract. Pre-contracting supports competitive bidding. It has been found to result in lower bids than those issued during emergency events when demand is high and resources are scarcer.

Based on a survey conducted as part of NCHRP Synthesis 438 Expedited Procurement Procedures for Emergency Construction Services[22] (2012), only 38% of the state DOT respondents had pre-positioned contracts in place. It should be noted that each state and local jurisdiction has its own laws or regulations that impact how contracting can be done for state agencies, and some do not allow for pre-positioned or standby contracts. Instead some states have developed lists of pre-qualified contractors to use to send out requests for bid when the need arises. Written procedures, guidance, checklists and even pre-printed forms may be part of a state emergency contracting process, especially in states that have more frequent natural disasters or emergencies.

Transportation Research Board Synthesis 390: Performance-Based Construction Contractor Prequalification[23] (2009) analyzed existing pre-qualification approaches in the U.S. and Canada and based on that analysis, developed a performance based approach. The approach includes performance, financial and managerial criteria and addressed three tiers: Administrative, Performance Based, and Project Specific. According to the authors, soft factors such as managerial competence and past performance are more important than hard factors, e.g. bonding and financial status. Recognizing that there could be issues to implementing the proposed approach, the authors recommended that there be transparency in all aspects of the implementation and that internal checks and balances be put in place to assuage concerns about consistency or fairness of the process.

[22] Gransberg, D. D., & Loulakis, M. C. (2012). Expedited Procurement Procedures for Emergency Construction Services (No. Project 20-05 (Topic 43-11)).
[23] Gransberg, D. D., & Riemer, C. (2009). Performance-based construction contractor prequalification (Vol. 390). Transportation Research Board.

Synthesis 46-11 reviewed the response and recovery actions of state DOTs following an event that impacted bridges. The Synthesis focused on type of hazards, damage detection techniques, and the availability of emergency response plans.

## D. Data Needs and Issues

Transportation Agency Self-Assessment of Data to Support Business Needs: Final Research Report[24] (2015) concisely summarizes the general state of data in transportation agencies.

> *State Departments of Transportation (DOTs) and other transportation agencies collect and manage large quantities of data. These data are used to enhance internal decision making processes, provide information to the traveling public and meet external reporting obligations. Because data collection and management can be costly, it is important to ensure that dollars invested in data are well spent. This involves not only collecting the right data, but ensuring that the data collected are transformed into meaningful information that can be used for policy making, resource allocation and operational decisions across the organization.*

To ensure that data collected are valuable, definitions of data terms with clarity and consistency are critical. Especially important to bridge risk assessment is the definition of "service disruption" as it applies to each evaluated hazard. With a clear definition, it becomes possible to quantify or classify the likelihood of disruption and the consequences of disruption as follows:

- Likelihood of service disruption depends on asset condition, physical characteristics (e.g. scour depth, redundancy, vertical clearance), indicators of adverse event probability (e.g. seismic zone, storm return period), presence of mitigation features, and overall assessment of the ability of the bridge to resist the hazard (resilience or its opposite, vulnerability). The methods for quantifying or classifying likelihood will vary by type of hazard.
- Consequence of service disruption depends on traffic volume; detour length; speed; magnitude of potential threat to safety, mobility or environment; size of the bridge; and other cost-related variables. The methods for quantifying consequences will depend on the definition of the service disruption, and the types of performance to be considered.

The concept of resilience is utilized in both the Florida and Minnesota approaches to address the need for a bridge performance measure that is focused specifically on the likelihood of service disruption. Other state DOTs such as New York are also incorporating the concept.[25]

There are many definitions of resilience that can be found, including one especially focused on engineering systems:

> *Resiliency is defined as the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must.*
> *(Allenby and Fink, 2005)*[26]

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[24] Spy Pond Partners, LLC. (2015) NCHRP Web Only Report 214 Transportation Agency Self-Assessment of Data to Support Business Needs: Final Research Report, Contractor's Research Report for NCHRP Project 08-92. Transportation Research Board, Washington, DC.

[25] See New York State Department of Transportation Bridge Safety Assurance Manuals: Hydraulic, Steel Details, Overload, Collision, Concrete Details, and Seismic, 2013.

In the Alaska geotechnical asset management approach[27], resilience is meant to be assessed based primarily on the properties of the asset and can be classified into three categories, focused on the ability of assets to refrain from disrupting service:

- Good: The asset is fully sufficient to resist anticipated hazards and normal deterioration according to current standards.
- Fair: The asset is sub-standard, and as a result there is elevated likelihood of mild-to-moderate disruption to mobility, safety, economic efficiency, or other performance objectives on the corridor.
- Poor: The asset is ineffective in resisting anticipated hazards, and as a result there is high likelihood of severe disruption to corridor performance objectives.

### Available Data Sources

Effective decision making requires the use of easily available data, with the use of currently available data being a significant cost saving. The analysis conducted for the FDOT study cited previously utilized the DOT's existing database on bridge inventory and inspection, historical records of damage after hazards and events along with NOAA's climatic data and data from FEMA. For the MnDOT approach cited above, the best bridge information available was a mix of bridge conditions described by NBI component data and element-level condition data.

Florida DOT research contains a good survey of information available for each type of hazard included in that research. Other research available on specific hazards includes NCHRP Report 761: Reference Guide for Applying Risk and Reliability-Based Approaches for Bridge Scour Prediction[28] (2013) which contains a practitioner's guide to the research results of NCHRP Project 24-34 focused on developing a risk-based methodology for calculating bridge pier, abutment, and contraction scour at waterway crossings that can be linked to Load and Resistance Factor Design (LRFD) approaches in use by structural and geotechnical engineers. NCHRP 12-85 Highway Bridge Fire Hazard Assessment[29] (2013) addressed fire damage to highway bridges and included guideline specifications for the evaluation of highway bridge structures following fire events.

The Alaska DOT GAM framework specified the data to be collected, mainly a condition-state inspection modeled after the AASHTO Bridge Element Inspection Manual. It also specified the analysis necessary to relate data to actions and desired outcomes, with risk of service disruption as the primary performance concern. In addition, it specified the means of presenting data, actions, and outcomes to various audiences. The developers of the framework recognized that in order for framework to be compatible with, and participate in, the agency programming process, it needed to provide investment candidate cost and benefit information compatible with what is produced by pavement and bridge management. The overall framework used in GAM for Alaska

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[26] Brad Allenby and Jonathan Fink. "Toward Inherently Secure and Resilient Societies," Science, vol. 309, No. 5737, August, 2005, p. 1034

[27] Under development by one of the research team members.

[28] NCHRP Report 761: Reference Guide for Applying Risk and Reliability-Based Approaches for Bridge Scour Prediction, Transportation Research Board of the National Academies, 2013

[29] NCHRP 12-85 Highway Bridge Fire Hazard Assessment, Transportation Research Board of the National Academies, 2013

DOT for project evaluation and for monetizing impacts of decisions and hazards closely follows the widely used methodology of AASHTO's Manual for User and Non-User Benefit Analysis for Highways, commonly known as the "Red Book" (AASHTO 2010). These methods are standard features of the functional improvement model in bridge management systems such as BrM, formerly known as Pontis.[30] An NCHRP synthesis Engineering Economic Analysis Practices for Highway Investment (2012)[31] discusses the widespread applications of these methods.

### Data Issues

As previously noted, clear definitions and terminology are important for correct application of the methods. It is necessary to be clear on the definitions of hazards, the cause-and-effect relationship between hazards and service disruption consequences, and the means of quantifying the factors which measure this relationship. Especially important is the definition of "service disruption" as it applies to each evaluated hazard.

In the Minnesota DOT bridge risk analysis, likelihood and consequence were very often combined into a single measure. For example, the scour rating of a bridge as assessed in current Mn/DOT practice describes both the likelihood of scour and the current amount of scour. As a result, a probabilistic likelihood/consequence table could not be developed for each individual hazard. As the Department's procedures and data sources improve over time, the computations of likelihood and consequence can become more distinct. Asset conditions as observed by inspectors in the field form the starting point. Various risk models are incorporated into the risk analysis such as likelihood models to relate historical adverse event frequency, deterioration, and resilience to the probability of service disruption; and consequence models to monetize mobility, safety, and recovery impacts. These models can be developed from an analysis of the Department's inspection and work history data, if available, or from research and expert judgment, if necessary. Ultimately, agency data and other sources would replace judgment in the models.

Existing data, especially those generated by non-transportation specific sources, may not be available in a format that is usable by transportation agencies. For example, the purpose of the U.S. DOT CMIP Climate Data Processing Tool is to process readily available climate data at the local level into relevant statistics for transportation planners. Also lacking is a fundamental understanding of the system-level behavioral characteristics and the potential impact of the identified conditions on the overall performance of the bridge superstructures.

Other challenges arise related to the large amount of data collected including those from routine biennial inspection, and the manpower and expertise required to interpret these data. Gathering and organizing data being collected using geographic information systems (GIS) has improved efficiency but more needs to be done.

Remote sensing technologies can have a potentially significant impact in the assessment of bridge conditions in the future. Implementation and effective utilization will likely require using sensors in a complementary manner such as coupling sensors with traditional assessment

[30] See Thompson et al 1999, Sobanjo and Thompson 2004

[31] National Cooperative Highway Research Program Synthesis 424:Engineering Economic Analysis Practices for Highway Investment, Transportation Research Board of the National Academies, 2012.

methodologies and utilizing temporal sensor outputs to enhance the bridge inspection and decision making process.

## Hazard Data Sources and Tools

Information on potential hazards, including probability and possible effects, can be obtained from the Federal Emergency Management Association (FEMA), State Emergency Management and Civil Defense Agencies, National Weather Service (NWS), Environmental Protection Agency (EPA), U.S. Department of the Interior, U.S. Geological Survey, U.S. Army Corps of Engineers, and Department of Natural Resources (DNR).

**FEMA 433: Using HAZUS-MH for Risk Assessment,** Federal Emergency Management Agency (FEMA) http://www.fema.gov/fema-433-using-hazus-mh-risk-assessment

**FEMA Map Service Center**

This Federal Emergency Management Agency source provides map information for a variety of users affected by floods, including homeowners and renters, real estate and flood determination agents, insurance agents, engineers and surveyors, and federal and exempt customers. There are flood maps, databases, map viewers, documents and publications providing comprehensive information. Further aspects of the site include FEMA issued flood maps available for purchase, definitions of FEMA flood zone designations, and information about FIRMettes, a full-scale section of a FEMA Flood Insurance Rate Map (FIRM) that users can create and print at no charge.

http://msc.fema.gov/webapp/wcs/stores/servlet/FemaWelcomeView?storeId=10001&catalogId=10001&langId=-1

**FEMA Flood Map Service Center (MSC)**

The FEMA Flood Map Service Center is the official public source for flood hazard information produced in support of the National Flood Insurance Program (NFIP). The MSC contains official flood maps, access a range of other flood hazard products, and tools for better understanding flood risk. subsection of

http://msc.fema.gov/portal/

**Interior Geospatial Emergency Management System (IGEMS)**

The Department of Interior Geosciences and Environmental Change Science Center IGEMS, which replaced the Natural Hazards Support System (NHSS), provides online maps containing the latest available information on earthquakes, earthquake shakemaps, streamflow data, floods, volcanoes, wildfires, and weather hazards.

http://igems.doi.gov/

**National Weather Service GIS Data Portal (NOAA)**

Current weather, forecasts and past weather data are available in Shapefile and other formats from the Data Portal. Hazards include tornados, hurricanes, rain, snowfall, floods and other weather related hazards.

http://www.nws.noaa.gov/gis/shapepage.htm

**Advanced Hydrologic Prediction Service (NOAA)**

The NOAA Advanced Hydrologic Prediction Service (AHPS) is a web-based suite of forecast products that displays the magnitude and uncertainty of occurrence of floods or droughts, from hours to days and months, in advance. The majority of the observed water level data displayed on the AHPS web pages originates from the United States Geological Survey's (USGS) National Streamflow Information Program which maintains a national network of stream gauges. In addition, real-time water level information is collected from other federal, state, and local stream gauge networks.

http://www.nws.noaa.gov/oh/ahps/

# Appendix B Proposed Guidelines

## Table of Contents

# 1. Introduction

Transportation Asset Management (TAM) is a strategic and systematic process of maintaining and managing infrastructure assets throughout their life cycle, focusing on business and engineering practices for resource allocation and utilization. It uses data and analysis to improve decision making, with the objective of providing the required level of service in the most cost effective manner (Gordon et al 2011).

In many agencies, risk management and asset management historically have been two distinct professional disciplines, each with its own data, techniques, jargon, and management methods. The premise of these Guidelines is that parts of risk management can be incorporated into asset management, so that risk concerns can be fully and appropriately considered in decisions about project priorities, resource allocation, and performance management.

The Guidelines are specifically targeted to risk **assessment**, as opposed to risk **management**. It is assumed that management functionality is to be provided by a bridge management system (BMS) and by the processes surrounding bridge planning and programming decisions. For successful implementation, it is necessary for the quantitative risk assessment process to feed into the analytical process of the BMS.

Given these requirements, it is important that the concepts and methods of asset management and bridge management guide the organizing framework of the methodology, and determine the specific form of performance measures and project benefit estimates used in priority setting and resource allocation. On the other hand, many of the data which are most useful for the assessment come from the domain of risk analysis, and carry the assumptions and terminology commonly used in that domain.

To make the Guidelines specific and implementable, AASHTOWare Bridge Management (BrM) is used as the target software for structuring the analysis methods. Not only is BrM the most widely-used bridge management system worldwide, but it is currently the only one that can be configured by an end-user system administrator to perform these calculations (Mirzaei et al 2014, Markow and Hyman 2009). However, developers of other BMS should also be able to implement the Guidelines with their software, and the models should be implementable in spreadsheets or other platforms that interface with a BMS.

All bridge management systems use one or more measures of condition as their basic measures of performance. A few, such as Pontis, the Canadian Stantec BMS, and Switzerland's KUBA, have models to estimate life cycle costs, safety, and mobility as additional performance measures. NCHRP Report 590 (Patidar et al 2007) contains a multi-objective framework that can consider up to 23 different measures derivable from National Bridge Inventory and Pontis data.

Risk is a unique performance concern, because the adverse events typically identified as "risks" can produce outcomes affecting all of the other performance concerns: such events can damage condition, increase life cycle costs, and reduce safety, mobility, and environmental sustainability (Figure 1). In considering how various hazards affect agency performance objectives, each agency will want to choose which of the boxes it may examine and check off, depending on institutional requirements and the situation of each specific bridge.

These guidelines provide a framework, methodology, and analysis procedures that can be implemented in bridge management systems in order to incorporate site-based risks into routine decision making.

| | Typical performance concerns | | | | |
|---|---|---|---|---|---|
| **Hazards** | **Condition** | **Life cycle cost** | **Safety** | **Mobility*** | **Environmental sustainability** |
| Earthquake | ❍ | ❍ | ❍ | ❍ | ❍ |
| Landslide | ❍ | ❍ | ❍ | ❍ | ❍ |
| Storm surge | ❍ | ❍ | ❍ | ❍ | ❍ |
| High winds | ❍ | ❍ | ❍ | ❍ | ❍ |
| Floods | ❍ | ❍ | ❍ | ❍ | ❍ |
| Scour | ❍ | ❍ | ❍ | ❍ | ❍ |
| Wildfire | ❍ | ❍ | ❍ | ❍ | ❍ |
| Extreme temperature | ❍ | ❍ | ❍ | ❍ | ❍ |
| Permafrost instability | ❍ | ❍ | ❍ | ❍ | ❍ |
| Overloads | ❍ | ❍ | ❍ | ❍ | ❍ |
| Over-height collisions | ❍ | ❍ | ❍ | ❍ | ❍ |
| Vehicle collisions ** | ❍ | ❍ | ❍ | ❍ | ❍ |
| Vessel collisions | ❍ | ❍ | ❍ | ❍ | ❍ |
| Sabotage | ❍ | ❍ | ❍ | ❍ | ❍ |
| Advanced deterioration | ❍ | ❍ | ❍ | ❍ | ❍ |
| Fatigue | ❍ | ❍ | ❍ | ❍ | ❍ |

* Includes concerns of congestion reduction, system reliability, freight mobility, and access

** Including vehicles with flammable and hazardous cargo

*Figure 1. Potential effects of hazards on typical bridge performance concerns*

## 1.1 Risk-based asset management

Federal legislation in 23 USC 119 mandates risk-based asset management processes and the development by every state of a risk-based asset management plan (TAM Plan). In proposed federal rules, Section 515.007(a)(3) elaborates that the TAM Plan must establish a process to identify the hazards affecting the movement of people and goods, assess the likelihood and consequences of adverse events, and evaluate and prioritize mitigation actions. Section 505.007(a)(2) specifies that the life cycle cost analysis is a quantitative network-level analysis that considers current and desired condition levels, asset deterioration, effects of adverse events, and treatment options over the whole life of assets (FHWA 2015).

Section 515.009(f) of the proposed rules specify that the TAM Plan shall cover at least a 10-year period, shall be made easily accessible to the public, and shall establish a set of investment strategies that improve or preserve condition and performance in support of the national goals in 23 USC 150(b). The regulation explicitly links the TAM Plan to the Statewide Transportation Improvement Program (STIP), which is the primary vehicle for programming of transportation projects. Section 515.009(h) says "A State DOT should select such projects for inclusion in the STIP to support its efforts to achieve the goals" of the TAM Plan.

All of the basic components of asset management and TAM Plans have been codified in various standards documents in recent years (Figure 2). In the United Kingdom, the authoritative source is Publicly Available Specification 55, volumes 1 and 2 (BSI 2008). In the United States, a basic framework is described in a financial management context in Government Accounting Standards Board Statement 34 (GASB 1999), and in a strategic planning context in Volume 1 of the AASHTO Guide for Asset Management (Cambridge et al 2002). A more detailed adaptation of the same principles is New Zealand's International Infrastructure Management Manual (IIMM, NAMS 2006). AASHTO has built on this concept in great practical detail with the AASHTO Transportation Asset Management Guide, Volume 2: A Focus on Implementation (Gordon et al 2011). Some general guidance is also provided in ISO 55000 (ISO 2014).

State TAM Plans developed so far have focused on two categories of risk:

- Systemic risks, such as future land use, staffing levels, staff qualifications, adequacy of information, program uncertainty, market conditions, leadership support, and climate change. These have effects across the entire transportation network.
- Site-based risks, where uncertain localized events can affect the performance of individual facilities.

The second of these risk categories is the focus of these Guidelines.

A key aspect of successful asset management implementation, brought out in the IIMM and the AASHTO Guide, is the notion of continuous improvement. A variety of human and automated ingredients need to be improved in tandem. The amount of progress that can be made in asset management tools is limited by the human and organizational readiness to use the technology, and vice versa. In a more tangible sense, the technology to produce quality TAM information depends on management willingness to accept asset management information in decision-making, to see the value and pay the cost of producing this information, including the data collection cost. Management acceptance, in turn, depends on the quality of information that can be produced. A small improvement in the decision making process must be matched by an incremental improvement in technology, which then spurs the next small improvement in decision making.

The data and models supporting risk analysis are imperfect, for the very reason that they focus on attacking uncertainty. They represent the cutting edge of improving the use of data and analysis in decision making. A recurring theme throughout these Guidelines is that methods are designed to be gradually improved by means of further research.

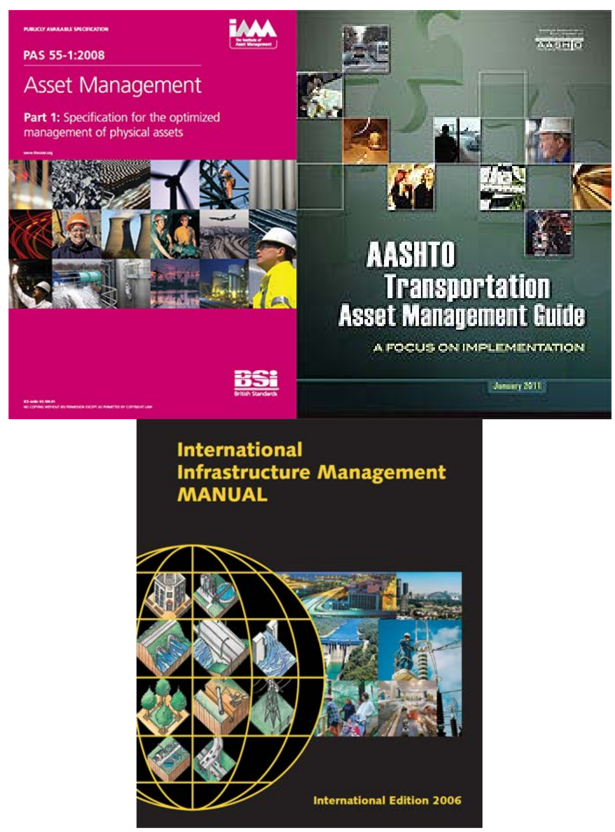


*Figure 2. International asset management standards*

## 1.2 Bridge management systems

A bridge management system (BMS) consists of formal procedures and methods for gathering and analyzing bridge data for the purpose of predicting future bridge conditions, estimating network maintenance and improvement needs, determining optimal policies, and recommending projects and schedules within budget and policy constraints. A BMS includes a network-level computerized database and decision support tool that supplies analyses and summaries of the data, uses models and algorithms to make predictions and recommendations, provides the means by which alternative policies and programs may be efficiently considered, and facilitates the ongoing collection, processing, and updating of necessary data (Hyman and Thompson 1993).

Bridge management systems typically contain a database of field-gathered data items covering:

Asset identification, location, and jurisdiction;
Structural classification and geometry;
Functional characteristics and utilization;
Risk assessments;
Condition data, at the bridge and element level;
Process management and planning metrics.

Most of the data items commonly found in bridge management systems are mandated by federal regulations, and subject to quality assurance processes and standards (FHWA 1995 and 2014). Compared to most transportation data resources, bridge data are highly uniform across the nation. These Guidelines rely on the mandated data items as much as possible, to ensure the relevance and acceptability of the methods. However, risk assessment information in the federal rules is relatively limited compared to the capabilities of many agencies. Many state DOTs are gathering their own risk assessment data, to provide information that is necessary for decision making. The Guidelines provide options to take advantage of this information where possible.

As of this writing, some 45 of the state DOTs are using the Pontis bridge management system, published by the American Association of State Highway and Transportation Officials (AASHTO). AASHTO is in the process of developing an all-new release of this bridge management system, called AASHTOWare Bridge Management. Many of the state DOTs have started to migrate their data and processes to the new system. However, the new software is not yet complete, so agencies still rely on Pontis for their decision support needs. Thus far only 25 of the states are participating in the AASHTOWare Bridge Management project, but it is widely believed that more states will eventually implement the new system. Private firms are also developing bridge management systems, and a few states use spreadsheets and other custom-developed tools to support their bridge management decision support needs.

To ensure maximum applicability, these Guidelines provide an emphasis on AASHTOWare Bridge Management. However, the methods are generic and can readily be implemented on other platforms, including spreadsheets. All of the relevant methods are fully documented here in order to ensure that private vendors and consultants can use them.

## 1.3 How to use this document

The tools described in these Guidelines are intended for decision support, not decision making. Considerable amounts of relevant data are available from a variety of sources, but they do not give a complete picture of risk and cannot give certainty to what is essentially uncertain. The models are useful, however, in that they harness the available data to make it more relevant to decision makers, to allow agencies to take maximum advantage of available data to make more informed decisions.

All risk assessment involves judgment and experience. Each decision maker has a unique set of experiences, which influence the way judgments are formed. Risk analysis by nature concerns events that may be very unusual, that may occur only rarely in a career and might not have been systematically measured by anyone. These Guidelines highlight several methods that use anecdotal or scant evidence, in combination with significant judgment. The purpose of these methods is to help agencies apply their collective experience and judgment in a consistent manner that can be documented, repeated, and improved over time.

Chapter 2 of these Guidelines provides some basic concepts and definitions that will apply throughout the volume. They are chosen for their ability to work within the frameworks of existing BMS and to be consistent with existing industry guidance.

Chapter 3 is the main procedure, which uses a set of worksheets to:

- Define hazard scenarios
- Estimate the likelihood of extreme events
- Estimate the likelihood of transportation service disruption, if an extreme event occurs
- Estimate the consequences of a service disruption if it occurs
- Estimate performance outcomes in a way that can be put to work in BMS to assist in priority-setting, resource allocation, and performance management.

Chapter 4 describes several ways in which the risk assessments can be used in risk management.

Chapter 5 provides additional detail on the significant analytical methods, which may be especially helpful for the developers of risk analysis tools that might build on, or improve, these Guidelines.

# 2. Bridge management system framework for risk

A key requirement for the Guidelines is that they can be implemented with the aid of bridge management systems. Therefore it must be structured so it fits within the analytical framework of these systems.

## 2.1 Risk in bridge management systems

Bridge management systems (BMS) typically provide functions to capture inventory and inspection data for each bridge, and then provide a set of mathematical models to analyze each bridge to forecast future conditions, performance, and costs (Figure 3). As a part of this functionality, BMS apply a set of decision rules to generate one or more alternative projects intended to relieve performance deficiencies and/or to reduce future costs. The software forecasts future performance and costs conditional on a project alternative and implementation year. A do-nothing scenario is also analyzed using similar models.

By comparing each project alternative with the do-nothing alternative, a project benefit is estimated. This benefit may be either positive or negative, and is subject to a set of definitions and reference criteria which need to be carefully defined in order to ensure consistent evaluation of all projects that the system is able to consider.

Typically a BMS will generate far more project candidates with positive benefits than can be funded under anticipated resource constraints. It then becomes necessary to prioritize. Practically all modern BMS use a benefit/cost ratio as the priority-setting criterion. An optimization algorithm is used to sort and select project candidates to fit a budget constraint and, in some cases (such as the software in NCHRP Report 590), a performance constraint. Given a list of selected projects in a fiscally-constrained program, the BMS proceeds to compute estimates of future network conditions and performance. Such estimates can be used for evaluating and comparing program outcomes, and for establishing performance targets and resource allocations.

Most fully-developed bridge management systems compute project benefits in Figure 3 using a life cycle cost analysis. In some cases, this life cycle cost analysis can include the user costs associated with functional deficiencies. Risk assessment that is fully integrated with this BMS analysis framework adds a second analytical engine to accompany the life cycle cost analysis in computing project benefits. The risk analysis uses information about the project and the effects of the project on future bridge characteristics, to compute a portion of the project benefit.

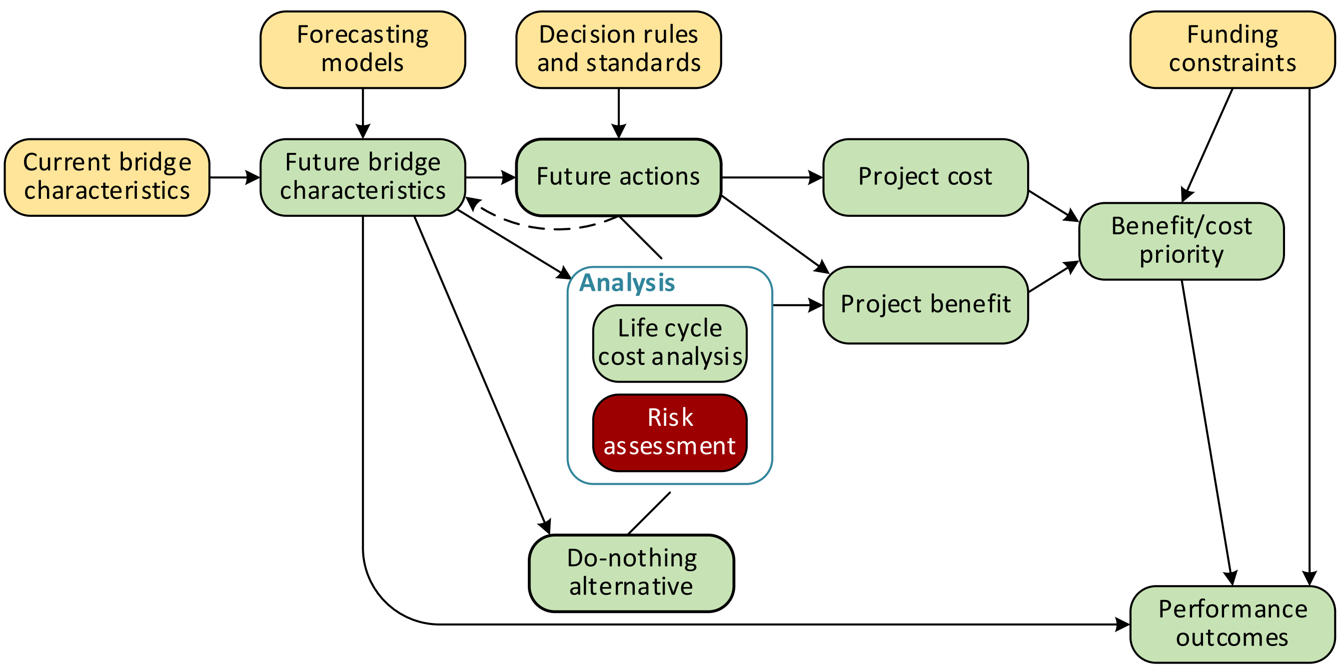


*Figure 3. Role of risk in a bridge management system framework. Colors distinguish inputs from results.*

## 2.1 Performance concerns and measures

Transportation agencies typically list their major goals and objectives in their enabling legislation, mission statements, strategic plans, or other broad policy documents that communicate with stakeholders and the public.

For transportation asset management in general, a set of national goals have been defined by the Congress in 23 USC 150(b):

> *(1) SAFETY.—To achieve a significant reduction in traffic fatalities and serious injuries on all public roads.*
>
> *(2) INFRASTRUCTURE CONDITION.—To maintain the highway infrastructure asset system in a state of good repair.*
>
> *(3) CONGESTION REDUCTION.—To achieve a significant reduction in congestion on the National Highway System.*
>
> *(4) SYSTEM RELIABILITY.—To improve the efficiency of the surface transportation system.*
>
> *(5) FREIGHT MOVEMENT AND ECONOMIC VITALITY.—To improve the national freight network, strengthen the ability of rural communities to access national and international trade markets, and support regional economic development.*
>
> *(6) ENVIRONMENTAL SUSTAINABILITY.—To enhance the performance of the transportation system while protecting and enhancing the natural environment.*
>
> *(7) REDUCED PROJECT DELIVERY DELAYS.—To reduce project costs, promote jobs and the economy, and expedite the movement of people and goods by accelerating project completion through eliminating delays in the project development and delivery process, including reducing regulatory burdens and improving agencies' work practices.*

Congestion reduction, system reliability, and freight movement are often considered together as "mobility." Elsewhere in the legislation, agencies are also called upon to minimize long-term costs. Each state DOT typically has a similar list of objectives. In asset management and risk management decision making, the most relevant concerns typically are cost, safety, mobility, and environmental sustainability.

### 2.1.1 Expressing performance

Performance measures are expressed in different ways for different management purposes. For pavements and bridges, it is common to define a condition index, or health index, on a scale of 0 (worst) to 100 (best). This is helpful when describing changes in condition over time, for one bridge or a group of bridges. It is also sometimes used in asset valuation applications as a proxy for depreciation (Shepard and Johnson 2001).

For expressing the condition of an entire asset inventory, FHWA has proposed the use of percent good and percent poor, where specific definitions are given to the terms "good" and "poor" based on measurable criteria (FHWA 2015).

For priority-setting, it is necessary to describe performance of the network as affected by a given bridge, which is different from describing the bridge itself or describing the combined condition of a group of bridges. Network performance relies on the public expectations for transportation service in terms of cost, safety, mobility, and sustainability. It must be commensurate with cost since it is used in a benefit/cost ratio, and so it is often treated as an economic quantity.

### 2.1.2 Recommended measures

Following the pattern established for condition, there is a need to describe the risk performance of each individual bridge based on bridge characteristics, and a need for a measure of the effect of risk on the network, compatible with the benefit-cost ratio.

Transportation agencies are increasingly concerned with transportation network resilience (Committees 2012, Hughes 2014), and asset management can help to maximize this characteristic by improving the resilience of individual assets. In Webster's dictionary, resilience is:

> *The ability to become strong, healthy, or successful again after something bad happens (Merriam-Webster 2016)*

Other definitions apply more closely to structural systems:

> *Resiliency[1] is defined as the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must* (Allenby and Fink 2005).
>
> *'Vulnerability' seems largely to imply an inability to cope and 'resilience' seems to broadly imply an ability to cope. They may be viewed as two ends of a spectrum (Levina and Tirpak 2006).*

"Internal and external change" can be interpreted in the context of bridge assets as changes caused within the asset

[1] "Resiliency" is an alternative spelling occasionally found in the literature, which has the same meaning as the more common spelling "resilience."

itself (i.e. normal deterioration) and change caused by external forces (natural extreme events, such as floods and earthquakes). "Maintain its functions and structure" can be interpreted as the avoidance of transportation service disruptions.

NCHRP Report 590 (Patidar et al 2007) proposed the use of a concept of utility, to represent the multi-objective assessment of performance of a bridge. Since resilience is a reflection of multiple bridge attributes, and it influences multiple network attributes, it is an appropriate application of utility. Report 590 explores a variety of ways to compute utility and to use measures of utility in bridge management systems. AASHTOWare Bridge Management has adopted one set of definitions as its means of expressing bridge performance.

The worksheets in Chapter 3 provide the format for computing resilience as a measure of utility. A more technical discussion in Chapters 4 and 5 explains in more detail how this computation is performed in typical bridge management system calculations such as in AASHTOWare Bridge Management.

As an economic measure for use in benefit/cost analysis, Chapter 3 also provides a method of estimating the social cost impacts of programming decisions, based on the same variables used in the resilience calculation. This method relies on research-based economic metrics that have been maintained by AASHTO in its Manual on User and Non-User Benefit Analysis for Highways, commonly known as the "Red Book." The method considers the direct cost of recovery from hazard events, as well as a consistent economic measure of safety, mobility, and emissions impacts of the events.

## 2.2 Hazards affecting bridges

The performance of bridges can be affected by a variety of natural and man-made hazards. They include:

**Earthquakes –** Seismic accelerations caused by natural or man-made forces can damage a structure and interrupt normal service. Operational decisions may be made to close an affected structure until such time as safety can be assured. As a result, the impact may be on mobility and cost rather than safety.

**Landslide –** Movement of unstable slopes may damage a bridge or render it unusable even in the absence of seismic events.

**Storm surge –** Offshore storms can exacerbate tide and wave action and inundate structures, causing scour or hydraulic pressure that can damage a structure. Some agencies may wish to include tsunami risk with this hazard since it may affect the same coastal bridges.

**High winds –** Tornadoes, hurricanes, and other high wind events may damage a structure from excessive wind pressure or atmospheric pressure differentials.

**Floods –** High water from excessive rainfall or snow melt may over-top structures, damaging them from hydraulic pressure, buoyancy, or scour. Some agencies may group this hazard with storm surge.

**Scour –** Steady erosion of bridge foundations may occur from long-term shifts in river currents or repeated flood events. Some agencies may group this hazard with floods.

**Wildfire** – Timber structures located in areas with natural fuels may be vulnerable to damage from wildfires. Some agencies also consider the service disruption from smoke, even if the structure is not damaged.

**Extreme temperature** – Unanticipated temperature swings may cause excessive bearing displacement or other movement-related damage.

**Permafrost instability –** Bridges or approaches founded on permafrost may settle if the subgrade becomes unstable due to warming. Bridges over debris flow channels may experience excessive earth or water pressure if the debris flows become more active because of freeze/thaw cycles.

**Overloads –** A bridge may be damaged if it is used by a vehicle that exceeds its safe load capacity.

**Over-height collisions** – A bridge may be damaged if struck by a vehicle whose height exceeds the vertical clearance of a roadway on or under it.

**Vehicle collisions** – A vehicular collision on or under a bridge may damage the structure if any of the vehicles strikes the bridge. This is a particular concern with fuel tanker trucks, which can generate very hot fires sufficient to permanently damage steel members.

**Vessel collisions –** A ship collision may damage a bridge or its protective systems.

**Terrorism/Violent Extremism** – Intentional damage may be caused by human activity, espcially from extremist organizations with political motivations.

**Advanced deterioration** – Excessive corrosion, cracking, or other defects may necessitate the premature restriction or closure of a bridge.

**Fatigue –** Bridge elements that experience repeated loading cycles over a long period of time may experience cracking, which can propagate very quickly under certain circumstances. Fracture critical bridges are of special concern.

This is a very long list of hazards. Based on resource availability and management concerns, agencies may choose to establish risk assessment processes for a subset of these risks, or may choose to identify a subset of hazards to be assessed for each specific bridge.

## 2.3 Analyzing risk in AASHTOWare Bridge Management

AASHTOWare Bridge Management (BrM) is the first commercially-available BMS that provides a framework for applying risk models (Bentley 2015). Although it has not been populated with such models as of current Release 5.2.2, it has features to allow an agency administrator to input such models without having to access the proprietary source code of the software. Inspectors can enter risk-related assessments of field conditions; analysts can use risk-related formulas to augment the benefit equation in benefit/cost analysis; and engineers can define treatments that mitigate risk. Since BrM is likely to be implemented by most of the state DOTs, it will receive the greatest amount of attention in these Guidelines. The developer of any other BMS using benefit/cost analysis can, in principle, modify their software to incorporate such models.

BrM provides a generic platform on which risk-related models can be implemented and used in decision-making, including in the benefit-cost analysis depicted above in Figure 3. The focus of this capability is the Risk Assessment record, shown in Figure 4, which is a part of what Figure 3 depicts as Bridge Characteristics. If a bridge has a risk-related concern associated with it, the inspector may add a corresponding Assessment record to that bridge in BrM (Figure 5). New Assessment records can be added any time a new assessment is performed. At any given time, the most recent assessment for a given Assessment type is considered to be the current status of the structure. The screen provides workflow information about the assessment and, most importantly, classifies the risk in terms of agency-defined hazard class, likelihood and consequence of service disruption, and affected deck area and traffic volume.

It is important to note that the BrM system and documentation offer no guidance on how hazard class, likelihood, or consequence are to be defined and assessed. These Guidelines will assist in making such decisions.

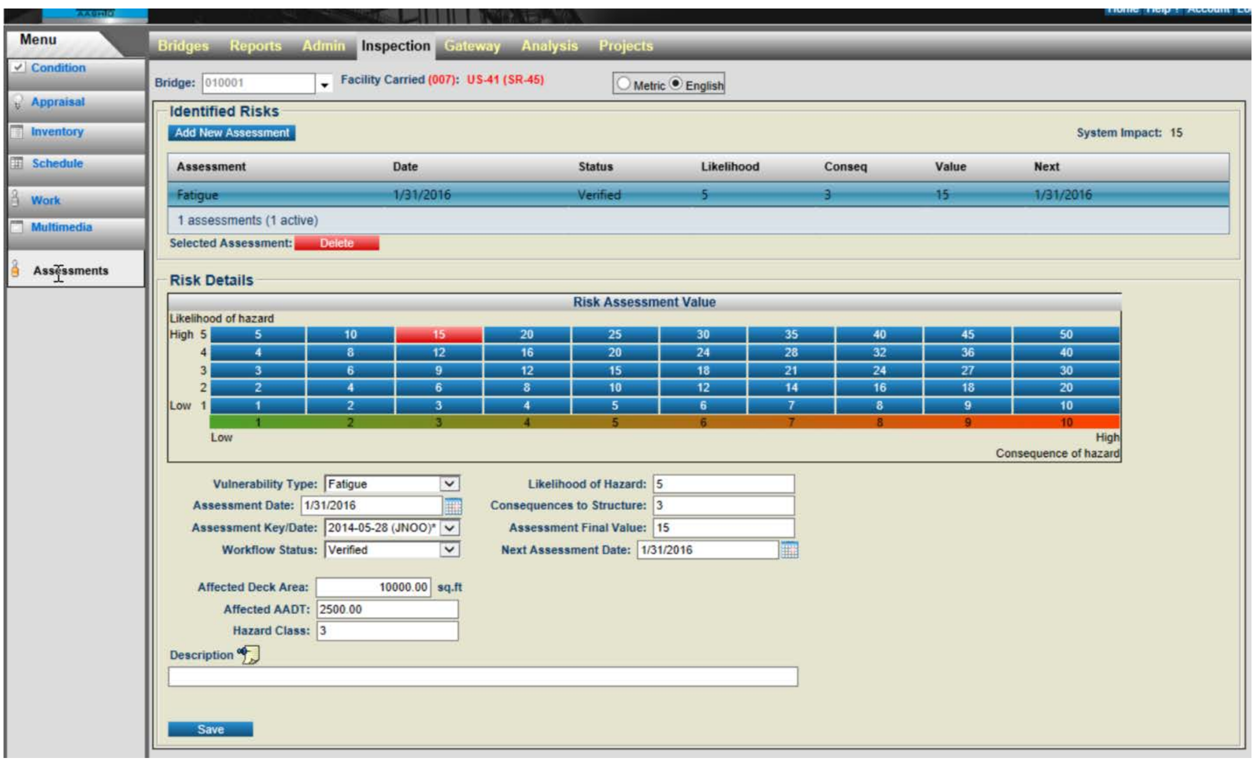


*Figure 4. Example risk assessment screen for one bridge in AASHTOWare BrM*

BrM comes configured for only a small number of Assessment types, but more can be added (Figure 6). The Assessment definition can be configured to set the range of values represented on the likelihood and consequence scales.

In order to use risk information in the calculation of project benefits, AASHTOWare BrM defines a mathematical formula called a Utility Function, based on the research in NCHRP Report 590. Utility is essentially a unitless composite performance measure that can combine condition, life cycle cost, safety, mobility, and any other performance concern. By convention, utility of 100 is best, and 0 is worst. Deterioration of a bridge may cause its utility to decline over time, and any kind of preservation or risk mitigation work will improve the utility. The improvement in utility is used in computing project benefit.

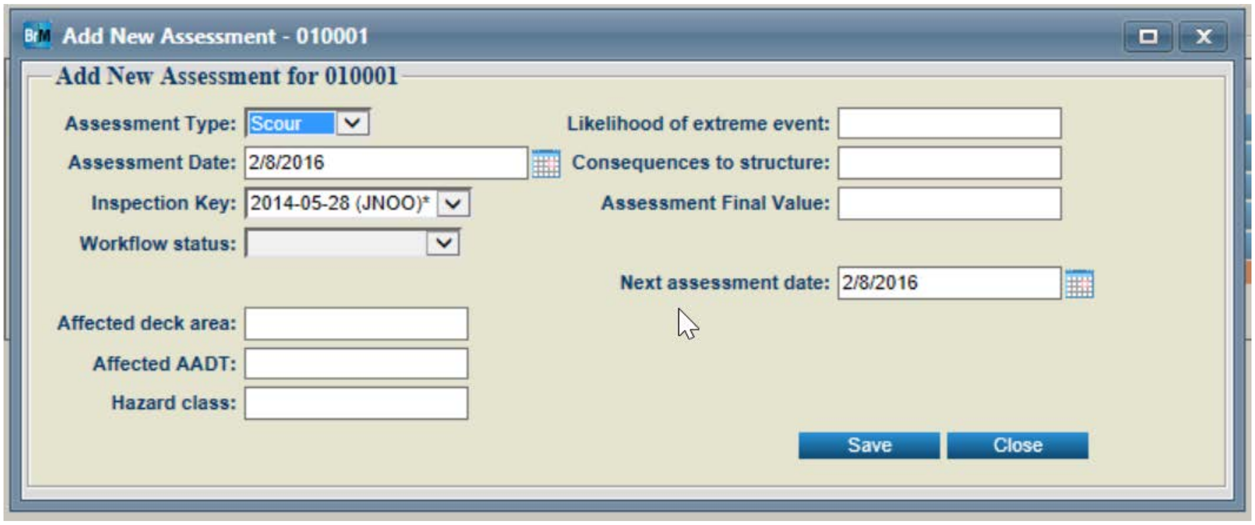


*Figure 5. Example screen to add an assessment record to a bridge in AASHTOWare BrM*

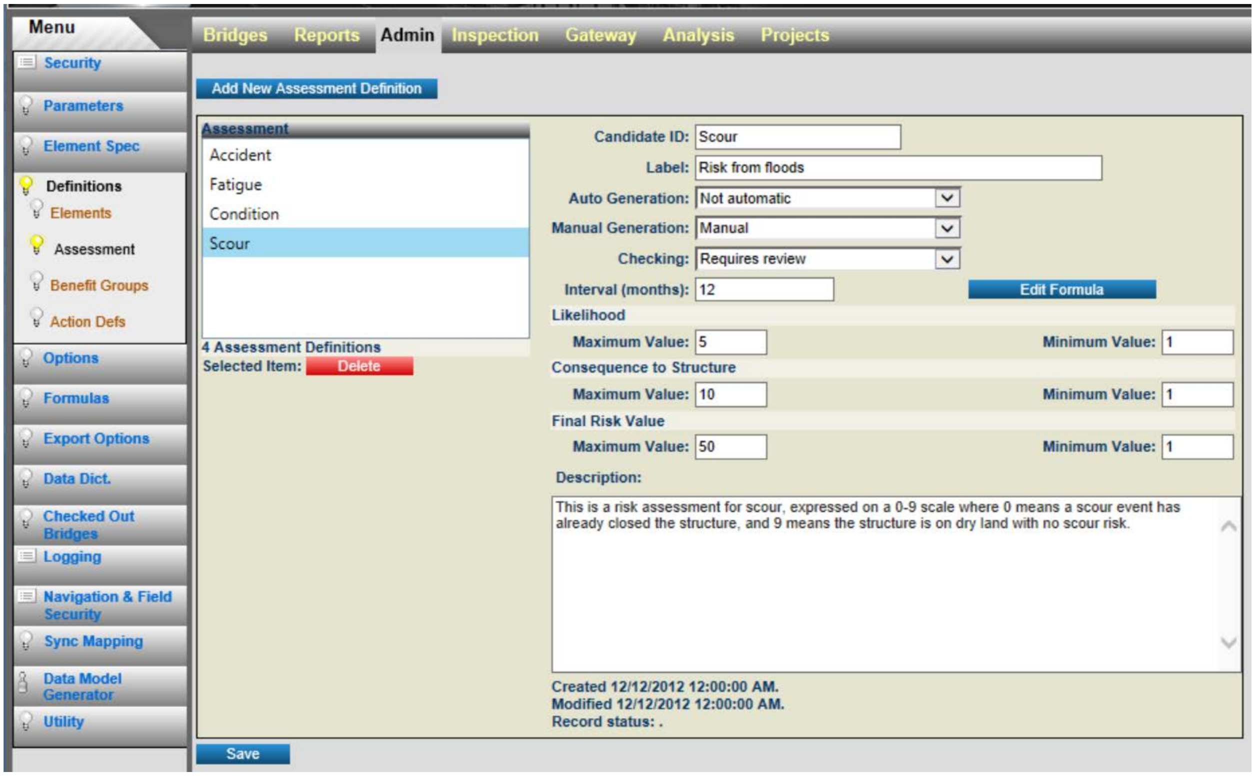


*Figure 6. Example assessment definition screen in AASHTOWare BrM*

Figure 7 shows the screen used in BrM to configure the utility function. The screen shows that there can be a tree-structured logic to the way utility is built up from separate performance measures and data items.

Each node in the tree depicted in Figure 7 is a computation based on information in the BrM database. The computation is specified by means of a formula editor (Figure 8). The utility associated with scour risk could be computed from a scour risk assessment and other data, such as the agency's scour classification for the structure. There are potentially a great number of ways the formula feature can be used to properly represent the effects of risk.

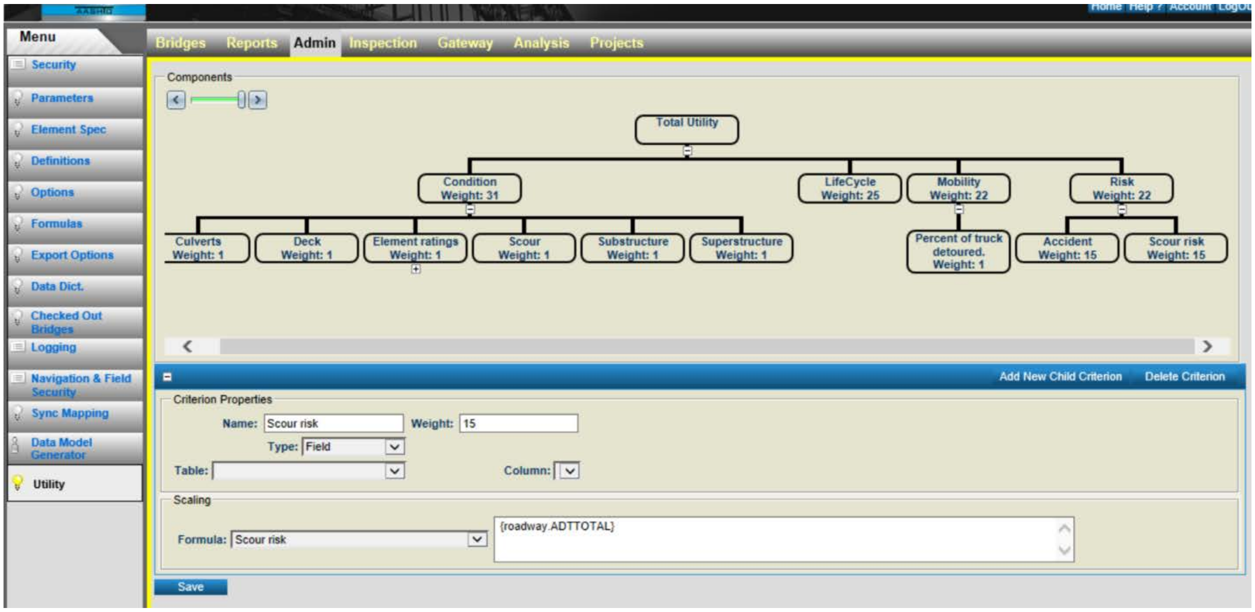


*Figure 7. Example utility function definition screen in AASHTOWare BrM*

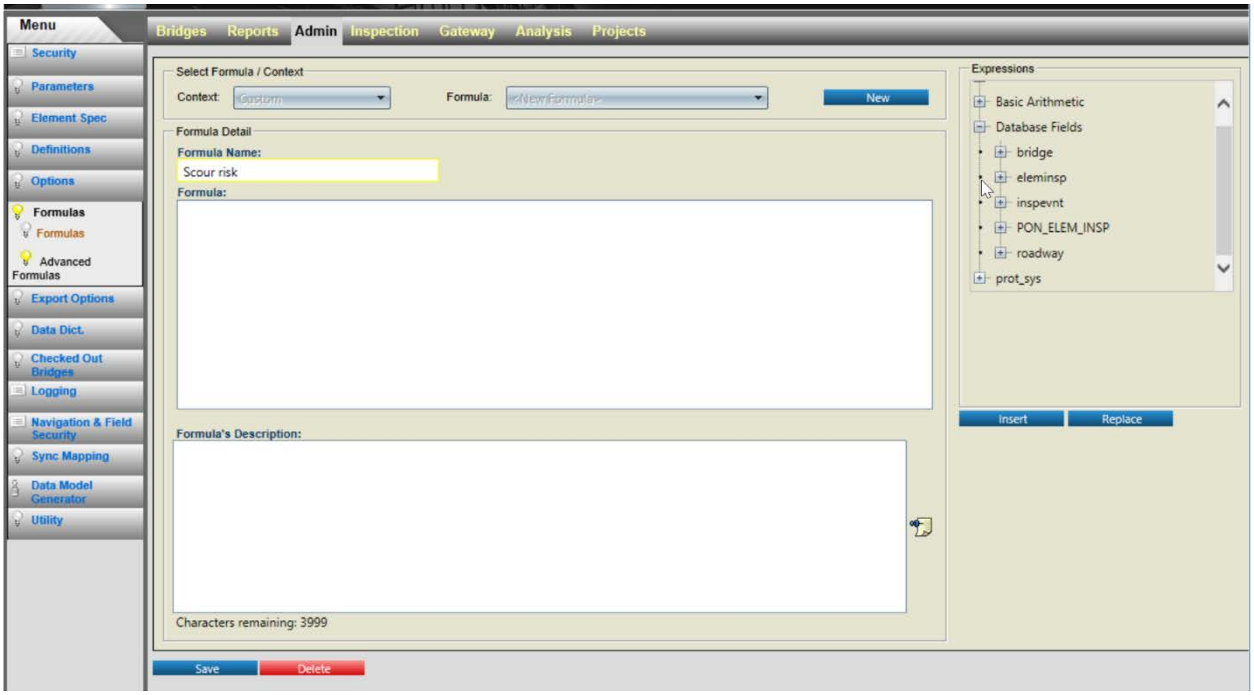


*Figure 8. Example utility formula screen in AASHTOWare BrM*

In AASHTOWare BrM, risk management is an integral part of project programming. Agencies define a variety of Actions (also known as "Flexible Actions") that can be applied to any bridge. Each Action may be incorporated into a Work Candidate if the bridge satisfies a set of warrant criteria that justify the Action. When such a Work Candidate is programmed as part of a project, then the Action produces benefits by potentially improving condition and improving the risk assessment score. Figure 9 shows the BrM screen used in order to define an Action, and Figure 10 shows the definition of a Benefit Group, which lists the various improvements in performance that an Action may cause. When a bridge's risk assessment score improves, then its Utility also improves. This improvement in Utility then contributes to the numerator of the benefit/cost ratio used for priority setting. In this way, agency actions are prioritized in order to reduce risk.

Using the capabilities visible on Figure 10, it is possible to define utility nodes that do not rely on field-gathered Assessments. For example, the risk of over-height truck collisions might depend on vertical clearance. A bridge raising action can be configured to change the bridge's vertical clearance to a design standard, say 16 feet. The utility calculation would use this revised bridge characteristic to compute a utility benefit from the action.

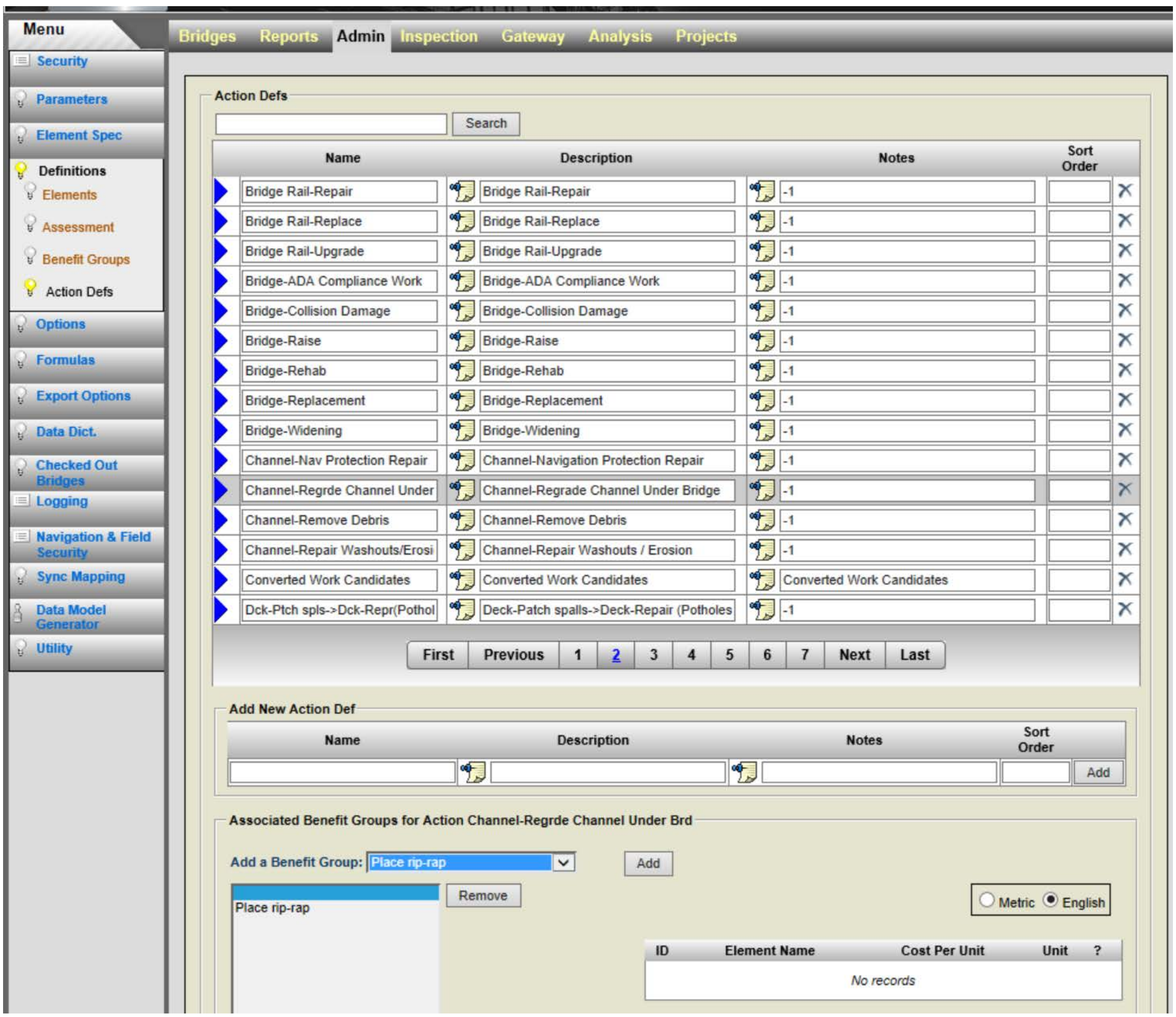


*Figure 9. Action definition screen in AASHTOWare BrM*

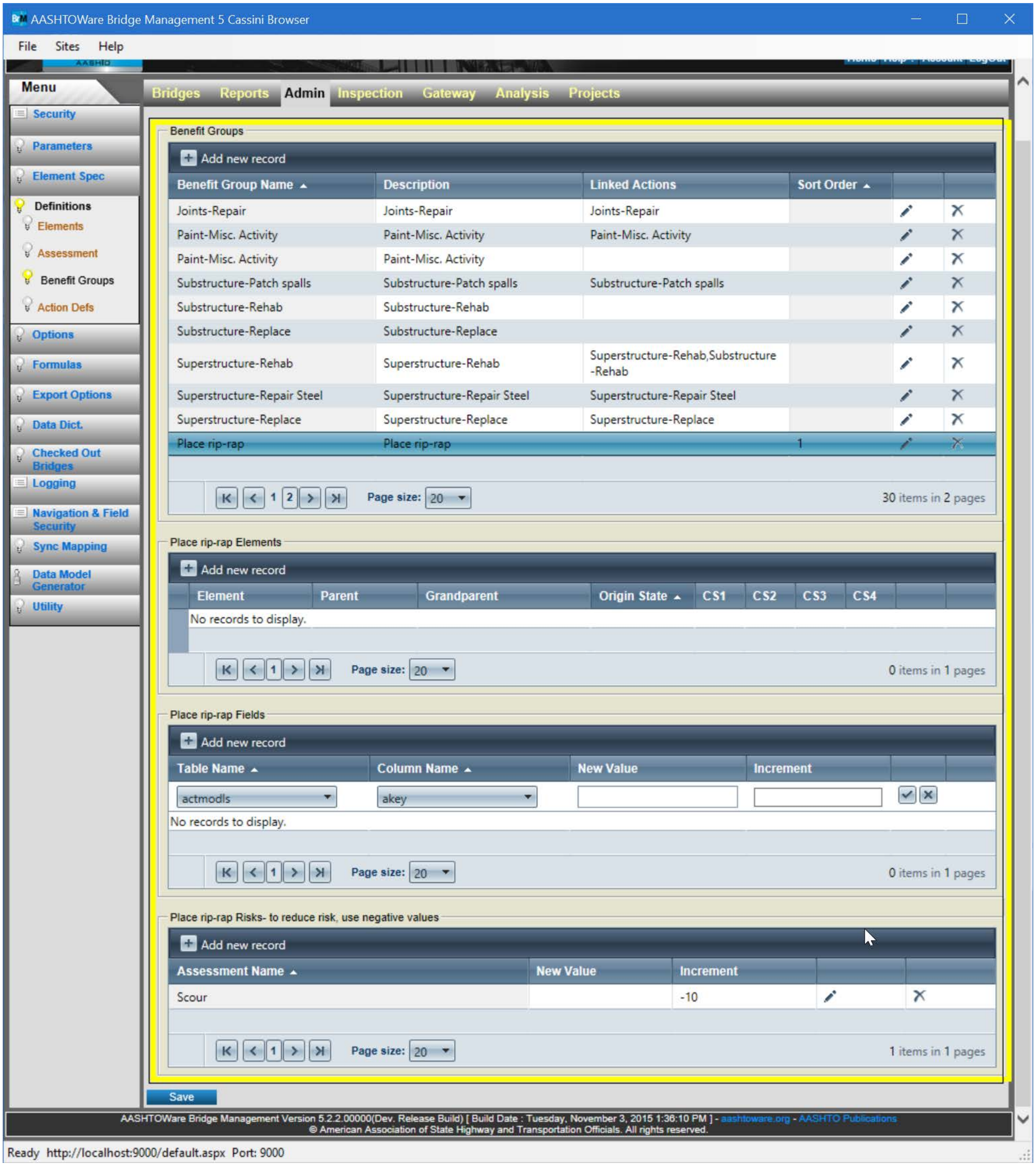


*Figure 10. Example benefit group definition screen in AASHTOWare BrM*

## 2.4 Glossary

**Bridge management system** (BMS) **–** Formal procedures and methods for gathering and analyzing bridge data for the purpose of predicting future bridge conditions, estimating network maintenance and improvement needs, determining optimal policies, and recommending projects and schedules within budget and policy constraints. A BMS includes a network-level computerized database and decision support tool that supplies analyses and summaries of the data, uses models and algorithms to make predictions and recommendations, provides the means by which alternative policies and programs may be efficiently considered, and facilitates the ongoing collection, processing, and updating of necessary data.

**Condition –** Measure of an asset's physical state as affected by deterioration and past maintenance and repair; can be expressed in terms of damage present (e.g., amount or percentage of cracking), an agency defined or standard scale (e.g., condition states 1 through 5; or good, fair, poor); often used in conjunction with "performance" when described in the context of performance-based processes.

**Consequence –** A summary measure of all impacts of an unexpected disruption in transportation service, as experienced by the agency, road users, non-users, and the environment.

**Extreme event** – An exogenous adverse effect on the transportation asset or system, causing an unintended loss of performance, caused by a natural or human activity, which is not caused by, or influenced by, agency decision making.

**Levels of service –** Classifications or standards that describe the quality of service offered to road users, usually by specific facilities or services against which service performance can be measured. Achievement of levels of service is measured by performance measures.

**Life cycle** – A length of time that spans the stages of asset construction, operation, maintenance, rehabilitation, and reconstruction or disposal/abandonment. When associated with analyses, life cycle refers to a length of time sufficient to span these several stages and to capture the costs, benefits, and long-term performance impacts of different investment options.

**Likelihood –** Characterization of the probability of an extreme event or of a service disruption.

**Performance –** Characteristic of an asset that reflects its functionality or its serviceability as perceived by transportation users. Section 4.4, below, describes how performance maximization relates to the social cost framework of a bridge management system.

**Performance management –**An ongoing process that translates strategic goals into relevant and detailed measures and targets that, along with resources, are continuously monitored to ensure achievement of published institutional goals.

**Performance measure** – An indicator, preferably quantitative, of service provided by the transportation system to users; the service may be gauged in several ways (e.g., quality of ride, efficiency and safety of traffic movements, services at rest areas, quality of system condition, etc.).

**Performance target –** Threshold value of a performance measure that an agency will strive to achieve to satisfy a policy objective.

**Resilience –** The capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must. Opposite of vulnerability.

**Risk –** The possibility of adverse consequences related to an asset from natural or man-made hazards. Generally, it consists of the likelihood of the hazard, the consequences of the hazard to the asset, and the impact of asset damage or malfunction on the mission of the asset or on life, property, or the environment.

**Risk assessment –** Characterization of potential effects of unexpected adverse events on performance.

**Risk management** – A process of identifying sources of risk, evaluating them, and integrating mitigation actions and strategies into routine business functions of the agency.

**Service disruption –** Loss of transportation system performance caused by an unexpected adverse event, caused by an extreme event and/or structure damage.

**Social cost –** The sum of long-term costs borne by the agency, users, non-users, and the environment, which are affected by a proposed decision.

**Transportation Asset Management** – A strategic and systematic process of maintaining and managing infrastructure assets throughout their life cycle, focusing on business and engineering practices for resource allocation and utilization. It uses data and analysis to improve decision making, with the objective of providing the required level of service in the most cost effective manner.

**Utility** – A unitless measure of the degree to which an asset or group of assets satisfies the objectives that the decision maker recognizes for that asset.

**Vulnerability –** The inability of a system to maintain its functions and structure in the face of internal and external change. Opposite of resilience.

## 3. Risk assessment

The following sections in this chapter present the recommended risk model in the form of a series of worksheets. While the worksheets could in principle be filled out by hand, most agencies will want to implement them either by entering corresponding data in AASHTOWare Bridge Management, or by creating a spreadsheet or other software to run the calculations. The worksheet format is intended to make the structure and data requirements as transparent as possible.

Each agency will want to choose which hazards and performance criteria to address, and customize the procedures to fit their own needs and resources. The modular worksheet structure is designed to allow agencies to plug in the modules which best fit their needs (Figure 11).

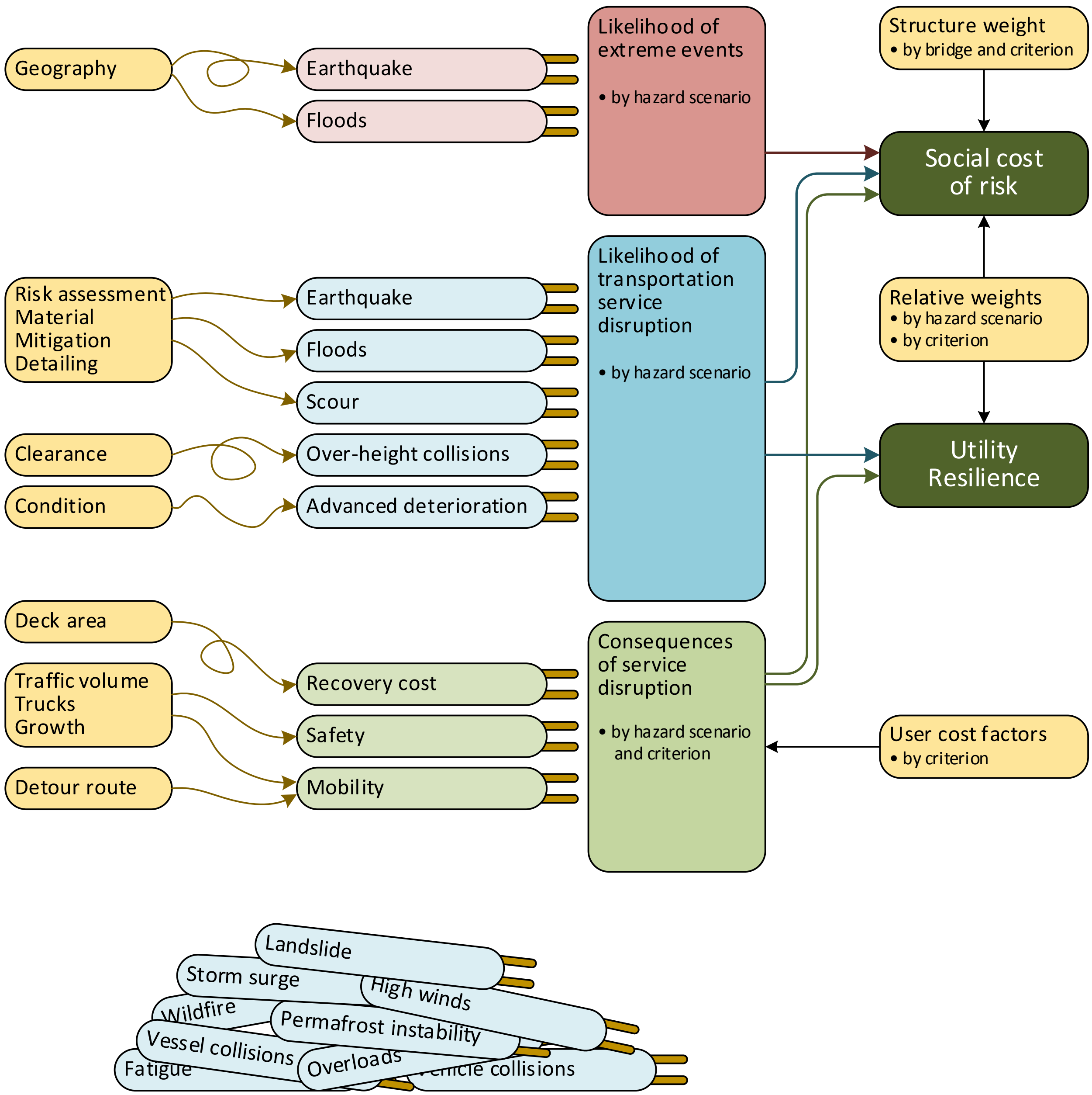


*Figure 11. Plug-in architecture of the recommended risk analysis. Colors distinguish inputs, results, and groupings of functionality.*

## 3.1 Define hazard scenarios and performance criteria

The disutility of an adverse event depends on the nature and magnitude of the hazard, and on the effect on each performance concern. In order to reflect these influences in a reasonable way, the following concepts are defined:

- Hazard scenarios, denoted in the equations using the subscript *h*, entail extreme events of a specific magnitude (if applicable) causing a defined impact on transportation service. For example, a hurricane of at least magnitude 4 that destroys a bridge.
- Performance criteria, denoted using the subscript *c*, represent agency objectives that may be compromised by a hazard scenario. Examples are condition, cost, safety, mobility, and environmental sustainability.

Each agency will select the hazard scenarios and performance criteria to be analyzed consistently across all bridges. Worksheet A provides a place to summarize these decisions for a given agency

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**Sheet A - Parameters**

Hazard scenarios

| ID | Class | Weight | Description |
|---|---|---|---|
| 1 | Eq-100 | 1.00 | 100-year earthquake, structure replacement required. |
| 2 | Fl-100a | 1.00 | 100-year flood, structure replacement required. |
| 3 | Fl-100b | 1.00 | 100-year flood, structure closed for 1 week for monitoring and scour mitigation. |
| 4 | Fl-500 | 1.00 | 500-year flood, structure replacement required. |
| 5 | OH-13.5 | 1.00 | Overheight collision for bridges up to 13.5' clearance, traffic detoured for one day |
| 6 | AD-0.9 | 1.00 | Advanced deterioration necessitates permanent load posting at rating factor 0.9 or below. |
| 7 | Fracture | 1.00 | A fracture causes partial failure of a structure, necessitating replacement. |
| 8 | | | |
| 9 | | | |
| 10 | | | |

*Please specify magnitude, damage severity, and service impact*

Performance criteria

| ID | Criterion | Weight | Description |
|---|---|---|---|
| 1 | Cost | 1.00 | Minimize recovery cost and excess life cycle cost |
| 2 | Safety | 1.00 | Minimize injuries and property damage |
| 3 | Mobility | 1.00 | Minimize excess travel time and vehicle operating cost |
| 4 | Environ | 1.00 | Minimize vehicle emissions and damage to environmental resources |

An important decision is the level of disruption that should be incorporated into the threshold for recognition of a hazard scenario. Some of the options are:

- The structure is damaged to at least a defined damage level, typically corresponding to the agency's distinction between routine work orders for repair, and programmed capital projects for mitigation, rehabilitation or replacement.
- Near-term or long-term life cycle costs are increased.
- Transportation service is disrupted, causing a loss of performance in terms of safety or mobility.
- Environmental resources or the property of others are damaged.

Any or all of the above could have a role in defining the criteria for a hazard scenario. For an understandable and consistent analysis, however, it is important to be consistent in definitions across all hazard types. The Guideline will be flexible in allowing agencies to adopt any reasonable set of criteria. However, the service disruption criterion is recommended for primary emphasis, for the following reasons:

- Most of the states having existing risk management capabilities as part of bridge management use this as their criterion.
- For most hazard classes, events that cause service disruption also cause structure damage.

- Service disruption events are typically regarded as more severe than damage-only events, and are more likely to be captured in historical records.
- Damage that is significant enough to disrupt service is typically more expensive to repair and more urgent than damage that does not disrupt service.
- Events belonging to some of the hazard types are not typically recognized as risk consequences unless they disrupt service. Examples are extreme temperature, settlement, advanced deterioration, and fatigue.

These Guidelines will normally use the term “service disruption” to characterize a hazard scenario but it should be understood that an agency may adopt different criteria.

The methods described in these Guidelines are designed for hazard scenarios that occur no more often than once a year on a given bridge. For adverse events that are more frequent, such as routine traffic accidents, other methods exist outside the scope of these Guidelines, such as user cost analysis of safety improvements (Thompson et al 1999).

In considering which hazards to include in the BMS risk analysis, the following questions should be considered:

1. Within the agency’s jurisdiction, does the hazard occasionally cause service disruptions or otherwise meet the criteria for a hazard scenario? “Occasionally” should be interpreted in a consistent way, such as once every 100 years for a given bridge.
2. Do the likelihood or consequences of the hazard scenario differ from one structure to another or one part of the jurisdiction to another? This likelihood could apply to extreme events, to structure damage, or to service disruption. Consequences could apply to any agency objective such as cost, safety, mobility, or environmental sustainability.
3. Does the hazard apply to a significant number of bridges? If only a handful of bridges can experience the hazard, then it might be more appropriate to perform site-specific analyses rather than including a model within the BMS.
4. Does the agency have treatments available to mitigate the hazard that would be programmed using the BMS? Bridge replacement is a relevant treatment, but in that case the question is, does the magnitude of the hazard make a difference in the choice of replacement or in the priority of replacement?
5. Is the hazard significant enough in decision making to justify the additional data collection, particularly field assessment that may be required in order to consider the hazard within the BMS? The worksheets later in this chapter will provide a clear indication of data requirements.

The level of detail represented in hazard scenarios can vary based on agency preference. It is likely that most agencies will want to keep the model simple by defining only a small number of scenarios to represent the broader range of possible adverse events. Increasing the number of scenarios increases the development and computational effort, but gives a more precise estimate of outcomes and risk. For example, if flooding is a particular concern then additional scenarios might be defined for that hazard, as in the Worksheet A example.

If a hazard scenario includes the occurrence of an extreme event, it is desirable to use the event magnitude for which agency’s structures are typically designed. For example, if bridges are typically designed to withstand a 100-year flood, then the 100-year flood is the extreme event magnitude to use, and the extreme event probability is one percent.

The weights provided in the middle column of Worksheet A are used in the social cost calculation described in the next section. In the example, all hazard scenarios and criteria are unweighted.

## 3.2 Risk assessment worksheet

Worksheet B (next page) is the place to record the results of all the calculations that follow, and to perform the final calculations of utility and social cost.

### 3.2.1 Likelihood of service disruption

The likelihood of service disruption in this framework varies by bridge, based on bridge characteristics, and also varies by hazard scenario. The consequence of service disruption also varies by bridge, based on bridge and network characteristics. It also varies by hazard scenario and performance criterion. More formally, the following symbols are defined:

$LE_{bh}$= likelihood of occurrence of the extreme event of given magnitude that is specified by hazard scenario $h$, estimated for bridge $b$ using the methods in Section 3.3.

$LD_{bh}$= likelihood of a specific magnitude of service disruption, conditional on the occurrence of the extreme event specified in hazard scenario $h$, estimated for bridge $b$ using the methods in Section 3.4, worksheets LD.

The total likelihood of hazard scenario $h$ on bridge $b$ is $LE_{bh} \times LD_{bh}$. The reasons for separating the extreme event likelihood from the service disruption conditional likelihood will become apparent shortly. These likelihoods are the probability of the indicated event occurring in any one year.

Likelihoods are described here as scalar probabilities, but agencies may want to use them as categories, for example, as ranges of return interval:

1. Not subject to flood
2. Flood return interval of >500 years
3. Flood interval of >100 years (outside 100-year zone)
4. Flood interval of <=100 years (inside 100-year zone)

This is especially useful if the BrM Assessment feature is to be used to record field judgments about the likelihood of disruption. Even if recorded in categories, representative probability values should be used in the utility and social cost calculations. For the previous example:

1. Probability is zero
2. Probability = 0.001
3. Probability = 0.0033
4. Probability=0.033

Here the representative values approximate the midpoints of the ranges of logarithm of probability represented by the categories.

In Worksheet B, the likelihood of extreme events and likelihood of service disruption are computed separately for each hazard scenario. The weights assigned to each hazard scenario are copied from Worksheet A, and the risk costs will be calculated as explained below. Later sections of this chapter will show how to estimate likelihoods for each type of hazard.

### 3.2.2 Consequence of service disruption

Consequences are defined as an economic quantity, as follows:

$CQ_{bhc}$ = consequence, estimated in dollars per disruption event, to performance criterion $c$ on bridge $b$, conditional on the occurrence of the service disruption specified in hazard scenario $h$, estimated using the methods in Section 3.5.

Consequences include the agency costs of disaster recovery as well as an economic value assigned to safety, mobility, and environmental impacts. The dollar value of consequences is typically estimated using economic models and normal agency cost estimation practices.

Consequences vary by hazard scenario and performance criterion. Similar to the situation with likelihoods, the consequence estimates can also be expressed in the form of ranges. To avoid having to make economic judgments in the field, the ranges can be expressed in the form of consequence ratios, such as:

1. Damage and service disruption are >= 75% of the maximum cost of total destruction of the bridge.
2. Damage and disruption >= 50% of maximum.
3. Damage and disruption >= 25% of maximum.
4. Damage and disruption < 25% of maximum

These assessments can then be converted to dollar values in a computation within the BMS. Consequence ranges should be defined on a linear scale, and midpoints should be used in the performance calculations.

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## Sheet B - Project summary

| | | | |
|---|---|---|---|
| Bridge ID | **010001** | | |
| Alternative | **Do nothing** | Deck area (sq.ft) | 20,000 |
| Program year | **2017** | Program cost ($000) | 12,345 |

| Roadways | On structure | | | | Under structure | | | |
|---|---|---|---|---|---|---|---|---|
| Func class | 11 - Urban interstate | | | | 14 - Urban other principal arterial | | | |
| Utilization | ADT | 54,000 | Trucks | 5.50% | ADT | 21,000 | Trucks | 3.00% |
| Roadway | Length (ft) | 200 | MPH | 55 | Length (ft) | 100 | MPH | 45 |
| Detour | Miles | 2.1 | MPH | 45 | Miles | 1.0 | MPH | 45 |

*From BMS data. If multiple roadways, use the total ADT and most significant roadway, projected to program year.*
*Length on-structure is bridge length. Length under-structure is bridge width..*

| Hazard scenarios | | Consequences ($000) | | | | Likelihood | | | |
|---|---|---|---|---|---|---|---|---|---|
| **ID** | **Scenario** | **Cost** | **Safety** | **Mobility** | **Environment** | **Extreme** | **Disruption** | **Weight** | **Risk ($k)** |
| 1 | Eq-100 | 12,345 | 50 | 6,000 | 600 | 1.00% | 5.00% | 1.00 | 9.50 |
| 2 | Fl-100a | 12,345 | 50 | 6,000 | 600 | 1.00% | 10.00% | 1.00 | 19.00 |
| 3 | Fl-100b | 100 | 0 | 2,000 | 200 | 1.00% | 20.00% | 1.00 | 4.60 |
| 4 | Fl-500 | 12,345 | 50 | 6,000 | 600 | 0.20% | 50.00% | 1.00 | 19.00 |
| 5 | OH-13.5 | 100 | 70 | 200 | 40 | -- | 5.00% | 1.00 | 20.50 |
| 6 | AD-0.9 | 50 | 0 | 200 | 40 | -- | 10.00% | 1.00 | 29.00 |
| 7 | Fracture | 12,345 | 0 | 6,000 | 600 | -- | 0.50% | 1.00 | 94.73 |
| 8 | | | | | | | | 1.00 | 0.00 |
| 9 | | | | | | | | 1.00 | 0.00 |
| 10 | | | | | | | | 1.00 | 0.00 |

*Use worksheet A to define the hazard scenarios and performance criteria.*
*See Section 3.5 for supporting computations of consequences.*
*See the Sections 3.3 and 3.4 for likelihood computations.*

| Risk cost and vulnerability | Cost | Safety | Mobility | Environment |
|---|---|---|---|---|
| Struc weight | 20,000 | 75,000 | 134,400 | 134,400 |
| Criteria weight | 1.00 | 1.00 | 1.00 | 1.00 |
| Social cost ($k) | 102.79 | 3.63 | 79.00 | 10.90 |
| Vulnerability | 5.1394 | 0.0483 | 0.5878 | 0.0811 |

*See Section 3.2 for these computations.*

| Risk analysis results | |
|---|---|
| Maximum unit risk cost: | 100 |
| Vulnerability index: | 0.0586 |
| Utility: | **94.14** |
| Social cost of risk ($000): | **196.31** |

### 3.2.3 Performance measures

The basic ingredients described in the preceding section are used in order to compute performance measures for decision support purposes. The following performance measures are needed:

$RC_b$ = Social cost of risk for bridge *b*. This variable should be structured and scaled so a savings in cost can be used in the benefit of a benefit/cost ratio for priority-setting, and so the BMS resource allocation and optimization models can minimize it network-wide. It may increase over time due to deterioration, traffic growth, or increased hazard likelihood; and it may decrease if an agency action improves bridge characteristics such that life cycle costs, risks, or road user inconvenience are reduced. It does not have to be expressed in dollars, but it should be proportional to the scale of representation of life cycle costs and social costs that are estimated in the preservation and functional improvement models in the BMS. Its values can range from 0 to positive infinity.

$U_b$ = Utility for bridge *b*. This variable should be structured and scaled so it can be understood as the degree of resilience of an individual bridge. It provides a uniform unitless scale for comparing the status of one bridge with other bridges, or for tracking performance of a bridge over time. In AASHTOWare BrM, this utility is the value computed by the Risk node of the Utility Model shown above in Figure 7. Its values can range from 0 to 100, where 0 is the worst possible performance and 100 is the best possible performance.

#### *3.2.3.1 Social cost*

In the recommended methodology, social cost of risk is the weighted sum of the social costs of all hazard scenarios and all performance criteria:

$$RC_b = \sum_h \sum_c RC_{bhc} \tag{1}$$

$RC_{bhc}$ = statistical expected value of weighted social cost, in dollars per year, of hazard scenario *h* on bridge *b* for criterion *c*.

$$RC_{bhc} = W_c \times W_h \times LE_{bh} \times LD_{bh} \times CQ_{bhc} \tag{2}$$

The variable $W_c$ is a weight given to each performance criterion in the cost equation. It should be 1.0 by default, but can be more or less than 1.0 to increase or decrease the contribution of a criterion in the calculation. For example, if $W_c = 1.2\ for\ c = safety$, then safety is given 20% additional cost in the risk calculation. Similarly, $W_h$ is a weight given to each hazard scenario. For example, if $W_h = 1.1\ for\ h = earthquakes$, then earthquakes are given 10% additional cost, perhaps to reflect the difficulty of incident response and the importance of supporting evacuation plans. The other variables in this equation are computed from bridge and network characteristics as introduced above and described more fully in later sections of this chapter.

The weights are established as network-wide parameters on Worksheet A, and copied to Worksheet B. In AASHTOWare Bridge Management, these weights are entered on the utility function definition screen (Figure 7 above). If an agency desires to use non-uniform weights for hazards or performance criteria, several group elicitation methods are available (Patidar et al 2007).

#### *3.2.3.2 Utility*

Utility is a concept related to social cost, but is designed to be used when making a direct comparison between bridges (disregarding their relative size), or when tracking performance over time. The scale is intentionally designed so each bridge can potentially score a perfect 100 or a worst-case 0 depending on its ability to resist hazards. In principle, agency actions should be able to improve this resilience to nearly 100 on any bridge, given sufficient resources.

Depending on the structure of the bridge management system, there may or may not be a mathematical relationship between utility and social cost. AASHTOWare Bridge Management, for example, is designed to compute utility first, at the work candidate level, and then convert this to social cost at the program level for computation of the benefit/cost ratio. Other systems may compute utility from social cost, or treat the two concepts as equivalent, or compute the two measures independently. Utility is meant primarily as a communication tool, while social cost is more rigorously defined for priority-setting and resource allocation.

To compute utility, it is common to first compute vulnerability as the product of likelihood and consequence of each separate adverse scenario for each separate performance criterion. Then the results are additive, and utility is:

$$U_b = (1 - V_b) \times 100 \tag{3}$$

The quantity $V_b$ can be called the vulnerability index, on a scale where 1.0 is maximum vulnerability and 0 is no vulnerability. Defining this concept of vulnerability involves several considerations:

- Generally the hazard scenarios considered in this type of analysis occur less often than once a year. Therefore the annual probability is generally on a scale of 0 to 1 already, and might be constrained to that scale. In most cases, however, these numbers are quite small.

- Consequences are dollar amounts that are in principle unlimited. However, what makes them unlimited is typically the deck area, traffic volume, and/or detour length, quantities that are not intended to be changed by risk mitigation actions.
- The maximum magnitude of vulnerability can vary by agency, depending on which types of risk it wants to include, and the magnitude of the risks, especially natural hazard risks. There is no universal endpoint of the vulnerability scale that would work for every agency.

Taking these considerations into account, one way to compute vulnerability is:

$$V_b = \frac{URC_b}{MaxURC} \tag{4}$$

$$URC_b = \sum_h \sum_c \frac{RC_{bhc}}{SW_{bc}} \tag{5}$$

The value $URC_b$ can be called the unit risk cost. It is the same risk cost as in equation 2 except that it is normalized to remove the effects of consequence scale. $MaxURC$ is determined by computing $URC_b$ for every bridge (or a representative set of bridges) in the database and finding the maximum value, which then defines the worst end of the vulnerability scale for the agency. $SW_{bc}$ is called the structure weight, and is computed in different ways for different performance criteria, as follows:

| | | |
|---|---|---|
| Cost | Deck area (sq.ft.) | (6) |
| Safety | Average daily traffic (ADT) | |
| Mobility | ADT × Detour length (miles) | |
| Environment | ADT × Detour length (miles) | |

Section 3.5 describes methods for computing consequences, which make it evident why these structure weight definitions are used.

After an agency first computes or estimates its $MaxURC$, this quantity is not likely to change very quickly over time. Therefore it might not be necessary for the agency to re-compute this constant unless it makes significant changes in its risk assessment process, such as by adding more hazards.

If a large number of hazards are included in the analysis, the additive approach represented by equation 5 may cause most bridges to be concentrated near the upper end of the utility range. This is because most bridges are subject to only a small subset of the possible hazards. Another way to look at it is that there will be a small number of bridges having multiple hazards, causing $MaxURC$ to be larger. Some possible approaches to this issue are:

- Combine similar hazards into a smaller number of categories before applying equations 4 and 5. For example, combine all natural hazards together into one, by adding their likelihoods and developing a common set of consequences. This will have the effect of compressing the range of possible outliers.
- It is permissible to allow outliers to exist and merely give them a utility of zero, or a negative utility. $MaxURC$ does not necessarily have to be the absolute minimum of $URC_b$, but can be set to cut off some of the outliers.
- Adopt a non-linear scale for utility, such as a sigmoidal curve or a set of categories, that are guaranteed mathematically to fall between 0 and 1 on the vulnerability scale.
- Use a multiplicative, rather than additive, method of combining hazard vulnerability indexes. Then the existence of multiple hazards will merely move the vulnerability index closer to 1.0 without passing 1.0.
- Recognize only the worst hazard on each bridge in computing vulnerability, and ignore the other hazards.

The advantage of having a linear relationship between vulnerability and social cost is the fact that social cost can be computed from vulnerability, which is a necessity for AASHTOWare Bridge Management and is desirable for keeping any BMS framework relatively simple. The concern about outliers and concentration of utility values near the top of the scale is purely a communication issue, and does not affect the applicability of the social cost equation for priority setting and resource allocation. If an agency desires to publish a more uniform scale of utility by using non-linear methods of computing it, this is perfectly valid, but in that case the utility calculation should be decoupled from the social cost calculation so priorities and resource allocations are not biased by the means of presentation.

#### 3.2.3.3 Other performance measures

In addition to the overall measures of social cost and utility, agencies may wish to have separate performance measures that correspond with broad agency objectives. These measures would be designed to be compatible with the measures used for other types of investments such as capacity and safety improvements. Like social cost, these measures can be based on likelihood times consequence, but might exclude the economic parameters. For example:

- A Safety measure based on excess accident counts or rates.
- A Mobility measure based on excess travel time or distance.
- An Environmental sustainability measure based on excess emissions.

These concepts are addressed in more detail in Section 3.5.

## 3.3 Methods for likelihood of extreme events

Certain hazards, specifically earthquake, landslide, storm surge, high wind, flood, wildfire, extreme temperature, and truck collisions, are triggered by short-duration events which are unusual and unexpected at any given site, but which occur with regularity across the inventory.

Some of these hazards, such as earthquakes, are so abrupt that they have unavoidable safety consequences. Others, such as floods, occur with some advance warning, allowing operational practices which may improve safety in exchange for a compromise in cost and/or mobility.

What all the extreme events have in common is that a portion of the likelihood of service disruption is unaffected by normal agency actions, but is related more to bridge location. This can be significant for decision making because, for example, an agency is powerless to prevent earthquakes, but can, with appropriate resource allocation, make programmatic decisions that increase the ability of bridges to resist earthquakes.

For most of the hazards in this category, geography is the primary variable in predicting likelihood of extreme events. In many cases, geographic data on hazard likelihood is readily available and can be used with minimal cost or difficulty by appropriately skilled and equipped staff. There may be cases, however, where anecdotal evidence or judgement may need to be relied upon.

Following the discussion of these geographic hazards, a separate section addresses certain man-made hazards, specifically truck and vessel collisions and sabotage, which have their own separate methods.

### 3.3.1 Natural extreme events

#### *3.3.1.1 Geographic analysis methods*

All of the geographic methods rely on an agency having a geographic information system (GIS) database with bridges accurately located. For most hazards, an approximate location within 1000 feet may be sufficient.

For flood and storm surge, the assessment of service disruption likelihood (in the following section) requires additional precision due to the need to determine accurate elevations at substructure locations. The Global Positioning System capabilities in common handheld devices such as cell phones are not precise enough for this purpose in determining elevations, so it is better to record this information from a topographic GIS database or US Geological Survey maps in advance of a site visit.

For a given agency, geographically-referenced data on extreme event likelihood may be available from several sources, described below. Ideally, such a data set has polygons representing zones where the event return period is estimated to be 100 years. This return period is most appropriate for bridge risk analysis since it is most likely to approximate or exceed the remaining service lifespans of most bridges. It is equivalent to a probability of one percent.

Such data sets often have polygons for alternative return periods such as 20 years or 500 years, which can form the basis for defining additional hazard scenarios if this is applicable for decision making. Alternative return periods also can be used for interpolating extreme event probabilities for locations between polygon boundaries.

Using a GIS software package such as ArcGIS, the analyst should overlay the hazard map with the bridge map, to determine for each bridge its approximate elevation (for storm surge, landslide, and flood), its location, the location of the hazard polygon, and the status of the bridge inside or outside the polygon. Interpolation of hazard probability between polygons is also performed at this stage, if desired.

Bridges by nature feature abrupt changes in elevation, so elevation maps might not be accurate enough to determine the exposure to an extreme event such as flood or storm surge. There are two approaches to accommodate this issue:

- Assess each bridge at the elevation indicated on the map for the roadway or waterway under the bridge. If a subsequent site visit is made (or in the next inspection), assess the site characteristics and reflect this in the determination of service disruption probability. For example, if a site visit determines that the bridge is not exposed to the level of flooding suggested by the map, reduce the service disruption likelihood to compensate.
- At the subsequent site visit, change the assessment of extreme event likelihood to reflect the evidence seen on-site.

While the second of these approaches has the potential to be more precise, it also introduces the potential for error and may make it more difficult to trace the source of errors. Therefore the first method is likely to be selected by most agencies.

The following sections describe sources of relevant geographically referenced hazard data:

**Earthquake**. The U.S. Geological Survey (USGS) National Seismic Hazard Maps (Figure 12) display earthquake ground motions for various probability levels across the United States and are applied in seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy. The National Seismic Hazard Maps are derived from seismic hazard curves calculated on a grid of sites across the United States that describe the annual frequency of exceeding a set of ground motions. Data and maps from the 2014 U.S.

Geological Survey National Seismic Hazard Mapping Project are available. The USGS Seismic Zone Maps are a probabilistic view (either 2% or 10%) that the ground acceleration will exceed the given value over 50 years. Depending on which model a state used, these would easily translate into the likelihood a state would use for their model.

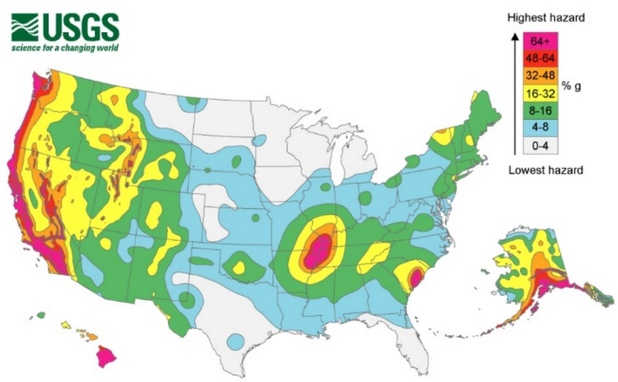


*Figure 12. USGS National Seismic Hazard Map (USGS 2011)*

Maps for available periods (0.2 s, 1 s, PGA) and specified annual frequencies of exceedance can be calculated from the hazard curves. Figures depict probabilistic ground motions with a 2 percent probability of exceedance. Spectral accelerations are calculated for 5 percent damped linear elastic oscillators. All ground motions are calculated for site conditions with Vs30=760 m/s, corresponding to NEHRP B/C site class boundary. There is also a FEMA HAZUS data set for earthquakes.

**Landslide.** Some jurisdictions that are especially sensitive to landslides have prepared hazard maps. As an example, hazard mapping will become statewide in Washington State following a 2015 state law (RCW 43.92.025), which also covers earthquake and tsunami. The law specifies lidar mapping and specifically requires estimation of likelihood and consequence, but does not mandate other parameters such as return period, leaving such decisions to the State Geologist.

Agencies that have slope inventories may be able to compute the total centerline length of road affected by unstable slopes. The polling method, discussed in Section 3.4.1.4, describes a way that can be used to generate a frequency of landslide incidents. These would be gathered for all roads, and not just bridges. If the total length of slope incidents is divided by the inventory length of slopes and the number of years covered by the poll, this will provide an estimate of landslide probability per foot of road. For a given bridge, multiply this by the total roadway length (on and under the bridge) to give a site-specific extreme event probability.

Agencies that experience debris flows from unstable slopes or freeze/thaw in deteriorating permafrost may identify extreme events associated with these phenomena that would be assessed in the same way as landslides.

**Storm surge**. Florida DOT conducted an analysis of hurricane risk using a FEMA HAZUS data set of high wind speed (Sobanjo and Thompson 2013). In a GIS this was associated with low elevations and coastal exposure to give an indication of storm surge vulnerability. Sheppard and Miller (2003) developed design storm surge hydrographs for the Florida coast (Figure 13). This report listed recommended values for peak storm surge heights and corresponding likelihoods (50 year, 100 year, and 500 years occurrence) at various locations.

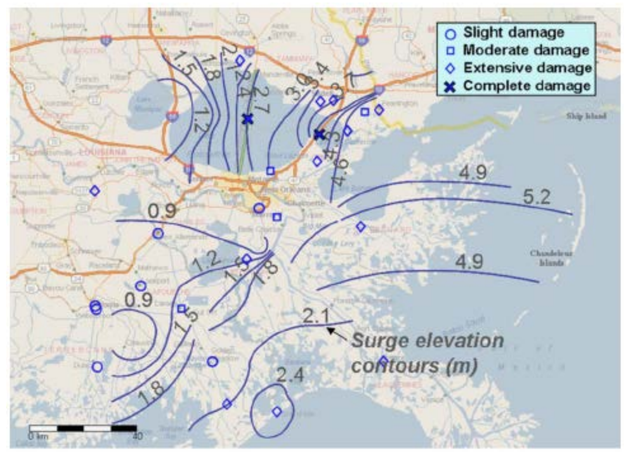


*Figure 13. Storm surge contours in Louisiana (Padgett et al 2008)*

The National Climate Assessment (2014) available online has regional forecasts with downloadable sea level rise maps. NCHRP Report 750 Vol 2 Climate Change, Extreme Weather Events, and the Highway System (2014) included sea level rise estimates by state. NOAA provides sea level rise and coastal flooding impacts data online along with a Sea Level Rise Viewer at the DigitalCoast website.

**High wind.** FEMA's HAZUS data set can provide high wind data that can be geographically associated with bridges. The National Weather Service GIS Portal has data on tornado occurrence across the USA.

**Flood.** The Federal Emergency Management Agency (FEMA) maintains the Digital Flood Insurance Rate Map Database, which depicts flood risk information and supporting data used to develop the risk data. The primary risk classifications used are the 1-percent-annual-chance flood event (100 year), the 0.2-percent-annual-chance flood event (500 year), and areas of minimal flood risk. Many state and county governments also maintain flood zone maps, which in many cases provide the basis for the FEMA maps. This information can be associated geographically with bridges to assign flood probabilities.

As is the case with other hazards discussed in this section, the assessment of extreme event likelihood should focus on characteristics exogenous to the bridge. Obviously the location of a bridge within a flood plain does not necessarily indicate that the bridge is vulnerable. But the determination of vulnerability should be made as part of the assessment of likelihood of service disruption, since it is influenced by agency actions.

National bridge inventory item 71, waterway adequacy, is partially defined by an indication of flood likelihood, and potentially could be used in place of data analysis. However, it is difficult for inspectors to assess the frequency of flooding without knowing more about the hydrology of the location. Flood maps are a more reliable source of this information.

**Wildfire.** Some states, and the US Forest Service, maintain geographic data sets on historical wildfire experience. Florida DOT used such a data set, from the Florida Department of Forestry, in its analysis (Sobanjo and Thompson 2013). The assessment of bridge vulnerability to fire and the proximity to fuels is made as part of the likelihood of service disruption.

**Extreme temperature.** The National Weather Service maintains maps of extreme temperature events across the nation. This information has been changing rapidly in recent years. The CMIP Climate Data Processing Tool, an Excel based tool developed for FHWA in 2015, utilizes the CMIP 3 and CMIP5 databases to create usable statistics for transportation planners for temperature and precipitation variables. The FHWA published Regional Climate Change Effects: Useful Information for Transportation Agencies in 2010 that had estimates of temperature, precipitation, sea level and storm activity for every region in the country – northeast, southeast, Midwest, Great Plains, southwest, Pacific Northwest, Alaska, Hawaii and Puerto Rico.

Most of the data sources described here are actively maintained and can change frequently. This makes it important to keep the assessment up-to-date. An updating interval of 4-6 years is suggested, for hazards that are addressed in the bridge management system.

#### *3.3.1.2 Historical research methods*

In the absence of geographically-referenced data, it may be possible in some cases to rely on anecdotal information, such as from news reports or studies taken from non-transportation domains. For example, the coasts of the Pacific Ocean and Gulf of Mexico have been subject to extensive monitoring and studies of sea level rise, which can be helpful in making judgments about the likelihood of storm surge and tsunami.

Earthquakes of magnitude severe enough to damage bridges are reliably reported in the media, so a systematic search may provide sufficient information on strength and frequency. Local knowledge or news reports of floods can form the basis for a localized assessment of flood likelihood, especially in combination with site evidence of past flooding. The same is true of landslides.

On the other hand, tornado and wildfire assessments should not rely on anecdotal reports since they are an unreliable indicator of future event locations.

### 3.3.2 Man-made extreme events

In assessing the likelihood of man-made extreme events, it can be difficult to separate exogenous factors from endogenous (agency-influenced) factors. The recommended approach is to assign a uniform extreme event probability across the entire network, then use the likelihood of service disruption to assess specific aspects of each structure that affect risk.

#### *3.3.2.1 Vehicle collisions*

For this hazard, the specific concern is the potential for tanker truck collisions to cause very hot fires that can damage steel or timber infrastructure. The Federal Motor Carrier Safety Administration maintains detailed statistics on crash frequencies for large trucks, including tankers and hazardous materials. The most recent report, as of this writing, was published in 2014 and reflected 2012 data (FMCSA 2014). This information provides an estimate of the number of crashes, which can be divided by vehicle-miles in order to relate crash risk with traffic volume. That rate would be applied to individual bridge roadways, on and under, to yield crash probability per year.

#### *3.3.2.2 Vessel collisions*

The frequency of vessel collisions can be very site specific, depending on the waterway, navigational aids, climate, and maritime traffic. As is the case with localized weather events, past incidents do not necessarily have any bearing on future risk. It may be possible to assess a generalized statewide baseline risk level for a class of waterways of interest, and then assess bridge protection features to estimate, using judgment, the likelihood of service disruption. The polling and analogy methods, described in the next section, would be an appropriate way to establish the baseline extreme event probability.

#### *3.3.2.3 Terrorism/Countering Violent Extremism*

Terrorists use a wide array of tactics and techniques in conducting an attack. There are unlimited possibilities as to the types of terrorist threats that could be brought against bridge structures. However, it is impossible to design all bridges to withstand all possible combinations of terrorist attacks that may occur. Below is a list of the most likely tactics and threats from the terrorists' perspective:

1. **<u>Vehicle borne Improvised Explosive Device</u>** (VBIED): These include both landborne vehicles (i.e. truck bombs) that would be deployed against components reachable by land and waterborne vehicles (i.e. boat bombs) that would be deployed against any components reachable by water.

2. **<u>Hand Emplaced Improvised Explosive Device</u>** (HEIED): These include contact explosive devices such as satchel demolition charges and shaped charges that are commonly used by military engineers and civilian demolition experts to precisely cut/sever structural member.

3. **<u>Non-Explosive Cutting Device</u>** (NECD): These include any non-explosive devices such as saws, grinders, and torches that can be used to cut/sever structural members.

4. **<u>Vehicular Impact</u>** (VI): Similar to the VBIEDs, these include both landborne and waterborne vehicles depending on the location of the component of concern.

5. **<u>Fire</u>**: Fire of sufficient size and duration can cause structural members to lose both their stiffness and strength. Thus, fire caused by a ruptured tanker truck on the deck of a bridge, adjacent to key components or in the water adjacent to piers or towers, is of great concern.

A Simple Bridge Security Checklist was created for use in assessing risk due to Terrorism for bridges. This checklist, described in the next section is an efficient method to establish a baseline level of risk.

## 3.4 Methods for likelihood of service disruption

### 3.4.1 Judgment-based estimation methods

Some of the methods described here are firmly grounded in research, but many are reliant on judgment or site assessments, or may be rough approximations. The framework is structured so the transportation community can improve the methods over time with further research, while preserving long-term continuity. When research-based metrics and methods are unavailable, one or more of the following techniques may help:

All of the applications of judgment in these Guidelines are meant to be temporary measures, to be used until such time as better data and research can be developed. Often the judgment-based worksheets can be evolved into templates for data items that the agency may want to consider adding to their existing information systems and data collection procedures.

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**Sheet LD - Assessment**

| | |
|---|---|
| Bridge ID | 010001 |
| Hazard scenario | Fl-100a |

Likelihood of service disruption

| Range | Probability | Use value | Check one |
|---|---|---|---|
| None | < 5 | 0 | ❍ |
| Low | < 35 | 25 | ❍ |
| Moderate | < 65 | 50 | ❍ |
| High | < 95 | 75 | ❍ |
| Certain | >= 95 | 100 | ❍ |
| | Specific probability (optional) | | |

### *3.4.1.1 Assessments*

AASHTOWare Bridge Management provides a feature, known as Assessments, which allows inspectors to assign a likelihood and consequence to any defined category of hazard. The screen for this feature is shown above in Figure 4. The ranges and scale can be defined in any way desired, but it is recommended that normally the likelihood ranges should represent relatively uniform ranges of probability from 0 to 100 percent, and the consequence ranges should represent uniform ranges of economic impact as a percent of the impact of total destruction of the bridge.

In the example at left, which is a 100-year flood scenario, the inspector would assess the probability that such a flood would disrupt transportation service. The inspector can either check one of the boxes, or can enter a value that differs from the values assigned to the boxes, provided it is between 0% and 100%.

Assessments may be performed as part of the normal bridge inspection process if inspectors are appropriately trained, or may be performed by a separate survey, for example, by a geologist for landslide hazards. BrM has a separate workflow for Assessments to accommodate special surveys such as this.

*Table 1. Example scoring table from Minnesota DOT (Thompson et al 2012)*

| | | SUPERSTRUCTURE CONDITION | | |
|---|---|---|---|---|
| | | Smart flag reduction | | |
| NBI Condition | | None | Case 1 | Case 2 |
| N | Not applicable | 100 | 100 | 100 |
| 9 | Excellent | 100 | 90 | 80 |
| 8 | Very good | 95 | 85 | 80 |
| 7 | Good | 90 | 80 | 60 |
| 6 | Satisfactory | 75 | 60 | 40 |
| 5 | Fair | 55 | 40 | 25 |
| 4 | Poor | 35 | 25 | 10 |
| 3 | Serious | 15 | 10 | 0 |
| 2 | Critical | 5 | 5 | 0 |
| 1 | Imminent fail | 0 | 0 | 0 |
| 0 | Failed | 0 | 0 | 0 |

### *3.4.1.2 Scoring tables or decision trees*

Agencies can develop judgment-based tables such as the example in Table 1. The main difference between this method and the previous one is that these scoring tables are developed in the office and are applied to each bridge automatically using BMS data, rather than by field assessment. Minnesota and New York have manuals based on these techniques, discussed in Chapter 5.

To work within a benefit/cost framework such as AASHTOWare Bridge Management, it is important that the variables used in the tables relate specifically to the likelihood of service disruption, so there is a clear separation from the extreme event likelihood and the consequences of disruption, which are estimated separately.

### *3.4.1.3 Analogies*

When a probability is to be estimated from judgment, it is often useful to compare the frequency or interval of unusual events with other types of events that are better understood. For example, if it is difficult to judge the probability of disruptions due to vessel collisions, it might be easier to think of it in terms of years between events, and then compare with a hazard category that has been measured more reliably such as hurricane frequency.

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**Sheet LD - Polling**

| | |
|---|---|
| Hazard scenario | **Wildfire-100** |
| District | **2** |
| Respondent | **IM456** |

Recollection of past incidents

Please jog your memory and list as many incidents as you can when wildfires damaged a bridge or otherwise forced a road closure or delay

| ID | Bridge | Year | Duration (days) | Impact |
|---|---|---|---|---|
| 1 | 010001 | 2014 | 30 | Destroyed |
| 2 | 157892 | 2012 | 1 | Closure |
| 3 | 150087 | 2009 | 45 | Destroyed |
| 4 | 226543 | 2009 | 14 | Damaged |
| 5 | 220007 | 2007 | 2 | Closure |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |

Scaling

| | | |
|---|---|---|
| 11 | How many years back can you reliably remember these incidents? | 10 |
| 12 | How many additional incidents do you believe occurred during this period? | 5 |
| 13 | Total number of bridges affected | 10 |
| 14 | Number of bridges in district *(from BMS)* | 1120 |
| 15 | Wildfire probability *(GIS analysis)* | 0.540% |
| 16 | Likelihood of service disruption *(Line 13 ÷ Line14 ÷ Line 11 ÷ Line 15)* | **16.534%** |

### *3.4.1.4 Polling*

For certain types of hazards where paper records may exist but are hard to locate, a promising approach may be to poll district maintenance officials to search their memory to identify recent events, and to estimate the number of additional such events in their jurisdictions that they didn't identify. They may be able to establish at least a range of reasonable frequency, as well as help in locating specific records where the affected bridge can be identified and other relevant information such as duration and recovery cost can be found. If the number of bridges exposed to a hazard can be identified separately (for example, from geographic analysis), then there is enough information to generate a reasonable probability estimate.

Often there will be multiple staff in a Department who can provide meaningful information. They should be asked to complete the worksheet separately, then their responses can be combined to compute an average estimate of service disruption likelihood. If there are inconsistencies among the responses, they should be discussed with the respondents to reach consensus on assumptions, and then the worksheets and averages should be updated accordingly.

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**Sheet LD - Allocation**

| | |
|---|---|
| Hazard scenario | **Wildfire-100** |
| Area considered | **Statewide** |

**Summary of historical analysis and polling**

| | | |
|---|---|---|
| 1 | Number of years covered (T) | 20 |
| 2 | Estimated total number of bridges affected over this period | 500 |
| 3 | Estimated total expenditure on incident recovery ($ million) | 15.3 |

**Scaling**

| | | Starting | Ending |
|---|---|---|---|
| 4 | Construction cost index | 5744 | 10092 |
| 5 | Number of bridges | 10,500 | 12,000 |
| 6 | Average deck area (sq.ft) | 10,540 | 11,965 |
| | | Growth rate | Multiplier |
| 7 | Number of incidents | 0.67% | 18.66 |
| 8 | Costs | 4.21% | 13.35 |
| 9 | Scaled estimate of annual number of incidents<br>*Line 2 / line 7 multiplier* | | 26.80 |
| 10 | Scaled total annual recovery cost ($/sq.ft)<br>*Line 3 × $1M / line 8 / line 9 / line 6* | | 3.58 |

**Bridge susceptibility**

| | |
|---|---|
| **Material** *(NBI 43 and 44)* | |
| Concrete, other | 0.2 |
| Steel, iron | 1 |
| Timber | 2 |
| **Fuel availability** *(to be assessed in the field)* | |
| Low | 0.2 |
| Medium | 1 |
| High | 2 |
| **Mitigation effectiveness** *(to be assessed in the field)* | |
| High | 0.5 |
| Medium | 1 |
| Low | 1.5 |

#### 3.4.1.5 Risk allocation

For hazards where both the disruption probability and recovery cost are difficult to estimate, another way to approach the problem is to start with a statewide estimate of the number of incidents or the amount of money spent on disaster recovery related to the hazard in question. This would be the total amount spent per year, averaged over a long time period, adjusted for inflation and for inventory growth. Information compiled by FEMA, by state government, and by news organizations may help to bracket this figure, and knowledge of past agency budgets would also bracket the range of possible expenditure levels. This total risk cost is then allocated among all the bridges in the inventory according to their size, utilization, and any other relevant bridge characteristics that the researcher is able to obtain. This analysis may then help to establish reasonable estimates for the unknown disruption probability and recovery cost.

The example worksheet shows the key inputs in the upper section, developed from historical research or polling of knowledgeable people. A construction cost index may be obtained from ENR (2016). FHWA also maintains a National Highway Construction Cost Index at FHWA (2016) which goes back to 2003. Information on past inventories may be obtainable from backups of NBI data or from FHWA.

Given starting and ending values, and a time period of T years, a growth rate is computed as follows:

$$r = \left(\frac{EndValue}{StartValue}\right)^{(1/T)} - 1 \qquad (7)$$

Typically the EndValue will reflect the status of the inventory at the time of the analysis, and StartValue will reflect the inventory T years earlier, as far back as data are available. To compute the growth rate for the number of incidents, StartValue and EndValue are entered on line 5. To compute the growth rate of costs, StartValue and EndValue are the products of lines 4, 5, and 6.

In order to estimate the current average annual disruption likelihood and cost from the long-term totals (lines 2 and 3), it is necessary to convert the growth rates to annuity factors. This is done as follows:

$$If\ r = 0\ then\ Multiplier = AF = T$$
$$Otherwise\ AF = \frac{1-(1+r)^{-T}}{r} \qquad (8)$$

The long-term number of bridges affected, and the long-term total cost, are divided by these multipliers to estimate the current annual rate of incidents and recovery cost, which is also known as the equivalent uniform annual cost. An estimate of recovery cost per square foot can be computed directly from this information as shown on the worksheet.

At this point line 9, the estimated annual number of service disruptions, describes the inventory as a whole. Different bridges will have different values of the likelihood of service disruption, depending on potentially many factors. The bottom portion of the worksheet suggests one way of assessing the relative likelihood in the field. There is no standardized assessment procedure for most hazards, so the agency should feel free to design the assessment in a way that reflects its typical experiences with each hazard.

What is important in these susceptibility factors is the relative probabilities among the categories. For example, the Material table estimates that timber structures are twice as likely to be damaged as steel structures. These are established from judgment. The absolute magnitudes of these factors are not important since they will be scaled in a later step to agree with historical incident frequencies.

If an assessment process is in place, the BMS database will have data related to the hazard assessment. In AASHTOWare Bridge Management, these items would be in the USERBRDG table or the Assessment tables. Table 2 shows how these might look, in an example database of only 12 bridges. In the example, the susceptibility factor for material is based on NBI items 43 and 44; fuel availability and mitigation effectiveness are assessed in the field, and wildfire probability is from the geographic analysis of likelihood of extreme events.

Relative likelihood is the product of the material, fuel, mitigation, and wildfire probability factors. It is therefore the combination of all the considerations that make a service disruption more likely on one bridge than another.

The final step is to scale the relative likelihood so the sum of predicted annual incidents agrees with the value calculated in line 9. First compute the estimated annual number of incidents on each bridge:

$$AllocInc = RelLike \times \frac{Line\ 9}{Sum\ of\ RelLike} \tag{9}$$

This should be a very small number since most bridges do not experience wildfires at any time in their life. Then compute the likelihood of service disruption:

$$LD_b = \frac{AllocInc}{Line\ 5\ \times LE_b} \tag{10}$$

The example shows the calculations for a 1/1000 sample of a typical inventory.

*Table 2. Example calculations for the risk allocation method*

| Example calculation for a 1/1000 sample of the database | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Predicted number of annual incidents in sample: | 0.0267956 | | |
| Bridge ID | Material | | Fuel availability | | Mitigation effectiveness | | Wildfire probability | Relative likelihood | Allocated incidents | Disruption likelihood |
| **Bridge ID** | **Matl** | **MatlName** | **Fuel** | **FuelName** | **Mitn** | **MitnName** | **Extreme** | **RelLike** | **AllocInc** | **Final LE** |
| 010001 | 0.2 | Concrete | 0.2 | Low | 0.5 | High | 0.540% | 0.0108% | 0.0000344 | 0.05% |
| 010003 | 1 | Steel | 1 | Medium | 0.5 | High | 0.540% | 0.2700% | 0.0008599 | 1.33% |
| 010004 | 1 | Steel | 2 | High | 1.5 | Low | 0.540% | 1.6200% | 0.0051596 | 7.96% |
| 010006 | 2 | Timber | 0.2 | Low | 1 | Medium | 0.540% | 0.2160% | 0.0006879 | 1.06% |
| 010007 | 0.2 | Concrete | 1 | Medium | 1 | Medium | 0.540% | 0.1080% | 0.0003440 | 0.53% |
| 010008 | 0.2 | Concrete | 2 | High | 0.5 | High | 0.540% | 0.1080% | 0.0003440 | 0.53% |
| 010009 | 2 | Timber | 1 | Medium | 1.5 | Low | 0.540% | 1.6200% | 0.0051596 | 7.96% |
| 010010 | 1 | Steel | 1 | Medium | 0.5 | High | 0.540% | 0.2700% | 0.0008599 | 1.33% |
| 010011 | 0.2 | Concrete | 0.2 | Low | 1.5 | Low | 0.540% | 0.0324% | 0.0001032 | 0.16% |
| 010012 | 1 | Steel | 0.2 | Low | 1 | Medium | 0.540% | 0.1080% | 0.0003440 | 0.53% |
| 010013 | 1 | Steel | 1 | Medium | 1.5 | Low | 0.540% | 0.8100% | 0.0025798 | 3.98% |
| 010014 | 2 | Timber | 2 | High | 1.5 | Low | 0.540% | 3.2400% | 0.0103192 | 15.92% |
| Total | | | | | | | | 8.4132% | 0.0267956 | |
| Scaling factor | | | | | | | | 0.3185 | | |

### 3.4.2 Recommended estimation methods

The following pages show example worksheets and supporting information for a variety of hazards that each agency may want to consider. Most agencies will select only a few of them for asset management. In most cases there are multiple ways of estimating the likelihood of service disruption, and there is considerable flexibility to adjust the analysis to suit an agency's needs.

The philosophy throughout these worksheets is to take advantage of all available data, and use judgment only to replace data that might be gathered later through improved inspection processes or research.

In designing customizations to these worksheets, remember the maxim, "all models are wrong, but some models are useful." Design your models so they shed light on risk management problems, in a way that is useful to you in making asset management decisions.

NCHRP 20-07 (378) Risk Analysis

**Sheet LD - Earthquake**

| | |
|---|---|
| Hazard scenario | **M9.0 Earthquake** |
| District | **Cascadia Subduction Zone - Oregon** |
| Respondent | **IM456** |

Recollection of past incidents

Please jog your memory and list as many incidents as you can when earthquakes damaged a bridge or otherwise forced a road closure or delay on or under a bridge

| ID | Bridge | Year | Duration (days) | Impact |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |

Scaling

| | | |
|---|---|---|
| | Number of Years (Single Event 300 Years) | |
| 11 | Total number of bridges in Zone | 2671 |
| 12 | Number of bridges not Damaged | 1651 |
| 13 | Number of bridges with Total Failure | 399 |
| 14 | Number of bridges Heavily Damaged | 621 |
| 15 | Total Number of damaged/failed bridges | 1020 |
| 16 | Number of M 9.0 in ~300 years | 1 |
| 17 | Earthquake probability *(regionally Assumed)* | 0.33% |
| 18 | Likelihood of service disruption | **12.72%** |

### *Worksheet LD-Earthquake*

Bridges in seismic areas may be vulnerable to earthquakes, which can destroy a bridge by means of ground shaking resulting in forces on the superstructure, substructure, deck and other bridge mechanisms. *Seismic Vulnerability Of Oregon State Highway Bridges - Mitigation Strategies to Reduce Major Mobility Risk* (Oregon State 2009) identifies state bridges potentially impacted from a seismic event, provides strategies for reducing risk, and provides mitigation recommendations. Geologic evidence has been discovered which supports a high probability of strong crustal earthquakes occurring in several areas throughout Oregon.

For bridge management it is necessary to estimate metrics that can be applied to probabilities of future seismic events. The method used in the Oregon research was to identify bridges in selected areas potentially impacted from a seismic event describing potential damage to State highway bridges from six representative earthquake scenarios that are thought most likely to occur. This would be bridges which may be damaged or closed by a seismic event. ODOT has chosen to be proactive in evaluating Oregon bridges and their performance level under the most common earthquake scenarios, utilizing the data collected from seismic hazard analysis conducted using REDARS 2 that simulates damage to bridges within a transportation network.

For agencies wishing to provide more detail in the service disruption likelihood estimate, a risk allocation process, as described in Section 3.4.1.5 above, may be appropriate. A historical cost analysis can be used to predict the number of significant seismic events in historic period of time, such as a single M9.0 event in 300 years. Then data from a detailed bridge analysis and bridge retrofits can be used to adjust the likelihood of disruption. Output from REDARS2 identifies bridge failures and those damaged, Line 3 and 4. This likelihood assessment could be expanded to include segments of highways containing a number of bridges.

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**Sheet LD - Landslide**

| | |
|---|---|
| Hazard scenario | **Landslide-100** |
| District | **2** |
| Respondent | **IM456** |

Recollection of past incidents

Please jog your memory and list as many incidents as you can when landslides damaged a bridge or otherwise forced a road closure or delay on or under a bridge

| ID | Bridge | Year | Duration (days) | Impact |
|---|---|---|---|---|
| 1 | 010001 | 2014 | 30 | Destroyed |
| 2 | 157892 | 2012 | 1 | Closure |
| 3 | 150087 | 2009 | 45 | Destroyed |
| 4 | 226543 | 2009 | 14 | Damaged |
| 5 | 220007 | 2007 | 2 | Closure |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |

Scaling

| | | |
|---|---|---|
| 11 | How many years back can you reliably remember these incidents? | 10 |
| 12 | How many additional incidents do you believe occurred during this period? | 5 |
| 13 | Total number of bridges affected | 10 |
| 14 | Number of bridges in landslide-vulnerable areas in the district | 1120 |
| 15 | Landslide probability *(GIS analysis)* | 0.540% |
| 16 | Likelihood of service disruption *(Line 13 ÷ Line14 ÷ Line 11 ÷ Line 15)* | **16.534%** |

### *Worksheet LD-Landslide*

In Section 3.3.1.1 above, methods were presented for estimating the risk of a landslide taking place at a bridge site. These can be based on a slope inventory or polling, considering the entire length of landslide-vulnerable roads (whether near a bridge or not) in order to develop a reliable probability estimate that is then scaled down to reflect the portion of roads occupied by bridges within these areas.

As a second step, it is necessary to determine the probability that service is disrupted, conditional on a landslide occurring near a bridge. Since most agencies do not have records of these events, the polling method is an appropriate way to develop an estimate. An example worksheet is shown at left, and the method is described above in Section 3.4.1.4.

In carrying out this analysis, a distinction is made between the road network in general, and landslide-vulnerable areas, which are typically roads adjacent to unstable, or potentially unstable, slopes. Roads that are not adjacent to unstable slopes are assumed to have zero landslide risk, but some judgment and geographic analysis are needed in order to identify situations, such as the 2014 Oso landslide in Washington State, where the road is a considerable distance from the slope but is still threatened. The extreme event probability (line 15 in the worksheet) is computed based on the population of bridges that are in the areas identified as vulnerable.

If an agency has a robust slope inventory and desires a more robust analysis, an area for future research is to analyze the relationship between bridge characteristics and bridge damage. With this information, a field assessment may be possible to further refine the likelihood of service disruption, to identify types of bridges where the benefits of mitigation might be especially high.

A few agencies have begun to develop geotechnical asset management programs that cover unstable slopes (Thompson et al 2016). These programs include a visual slope assessment addressing:

- Roadway displacement or slide deposit: assesses the direct effect on the roadway surface of earth movement, combining the effects of all relevant condition characteristics and mitigation features.
- Length of affected roadway and roadway impedance: assesses the geometry of the site.
- Movement history: assesses the combined effect of geological character, climate, hydrology, and permafrost quality.

For bridges, slopes of particular concern are unstable approach embankments and debris flow sites.

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## Sheet LD - Surge

| | |
|---|---|
| Hazard scenario | **Surge-Cat1** |
| District | **2** |
| Respondent | **IM456** |

### Recollection of past incidents

Please jog your memory and list as many incidents as you can when storm surge damaged a bridge or otherwise forced a road closure or delay on or under a bridge

| ID | Bridge | Year | Duration (days) | Impact |
|---|---|---|---|---|
| 1 | 010001 | 2014 | 30 | Destroyed |
| 2 | 157892 | 2012 | 1 | Closure |
| 3 | 150087 | 2009 | 45 | Destroyed |
| 4 | 226543 | 2009 | 14 | Damaged |
| 5 | 220007 | 2007 | 2 | Closure |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |

### Scaling

| | | |
|---|---|---|
| 11 | How many years back can you reliably remember these incidents? | 10 |
| 12 | How many additional incidents do you believe occurred during this period? | 5 |
| 13 | Total number of bridges affected | 10 |
| 14 | Number of bridges in storm surge-vulnerable areas in the district | 1120 |
| 15 | Storm surge probability *(GIS analysis)* | 0.540% |
| 16 | Likelihood of service disruption *(Line 13 ÷ Line14 ÷ Line 11 ÷ Line 15)* | **16.534%** |

*Worksheet LD- Surge*

Bridges in hurricane-prone coastal areas may be vulnerable to storm surge, which can destroy a bridge by means of lateral pressure on the superstructure, buoyancy, scour, and other mechanisms. Florida's risk study (Sobanjo and Thompson 2013) discusses several reports that quantify the structure damage and service disruption from individual storms, especially the work of Jamie Padgett.

For bridge management use it is necessary to estimate metrics that can be applied to probabilities of future storms. The method used in the Florida research was to survey district engineers to record their recollections of specific bridges that were damaged or temporarily closed by hurricanes. Inspection and repair reports were then accessed to determine the specific types of damage, closure duration, and recovery costs. For the period of time during which the inspectors' recollection could be relied upon, the geographic analysis of FEMA data was used to determine the total number of bridges that were exposed to the extreme event, as a means of estimating the disruption probability. The Florida researchers used five hazard scenarios corresponding to five Saffir-Simpson storm categories.

For agencies wishing to provide more detail in the service disruption likelihood estimate, a risk allocation process, as described in Section 3.4.1.5 above, may be appropriate. The polling approach or a historical cost analysis can be used to predict the total number of incidents, then data from a field assessment can be used to adjust the likelihood for individual bridges. The field assessment could consider scour vulnerability, elevation of the bottom of the superstructure, approach road vulnerability, embankment protection, and other relevant criteria.

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**Sheet LD - Wind**

| | |
|---|---|
| Hazard scenario | **High wind-100** |
| District | **2** |
| Respondent | **IM456** |

Recollection of past incidents

Please jog your memory and list as many incidents as you can when tornadoes or other high winds damaged a bridge or otherwise forced a bridge closure or delay

| ID | Bridge | Year | Duration (days) | Impact |
|---|---|---|---|---|
| 1 | 010001 | 2014 | 30 | Destroyed |
| 2 | 157892 | 2012 | 1 | Closure |
| 3 | 150087 | 2009 | 45 | Destroyed |
| 4 | 226543 | 2009 | 14 | Damaged |
| 5 | 220007 | 2007 | 2 | Closure |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |

Scaling

| | | |
|---|---|---|
| 11 | How many years back can you reliably remember these incidents? | 10 |
| 12 | How many additional incidents do you believe occurred during this period? | 5 |
| 13 | Total number of bridges affected | 10 |
| 14 | Number of bridges in the district | 1120 |
| 15 | Wind event probability *(GIS analysis)* | 0.540% |
| 16 | Likelihood of service disruption *(Line 13 ÷ Line14 ÷ Line 11 ÷ Line 15)* | **16.534%** |

*Worksheet LD- Wind*

Estimation of service disruption likelihood for high winds would use the same methods as described above for storm surge. It is especially helpful to develop geographic zones or polygons having uniform probabilities of damaging events, such as a 100-year storm. The characteristics of that storm should be taken into account when identifying high wind events that have caused service disruptions, since the service disruption probability is conditional on the occurrence of the hazard scenario.

It is uncommon for agencies to have inventory-wide risk management programs for high winds, but it is common for agencies to plan mitigation actions on specific structures found to have unusual wind response behavior. The methods described here can be used to estimate the economic benefit of such mitigation actions, as part of benefit/cost prioritization of proposed investments. This may be helpful if the funding for a needed mitigation action is in doubt.

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**Sheet LD - Flood**

| | | |
|---|---|---|
| Hazard scenario | **Flood-100** | |
| Area considered | **Statewide** | |

| Summary of historical analysis and polling | | |
|---|---|---|
| 1 | Number of years covered (T) | 20 |
| 2 | Estimated total number of bridges affected over this period | 500 |
| 3 | Estimated total expenditure on incident recovery ($ million) | 15.3 |

| Scaling | | | |
|---|---|---|---|
| | | Starting | Ending |
| 4 | Construction cost index | 5744 | 10092 |
| 5 | Number of bridges | 10,500 | 12,000 |
| 6 | Average deck area (sq.ft) | 10,540 | 11,965 |
| | | Growth rate | Multiplier |
| 7 | Number of incidents | 0.67% | 18.66 |
| 8 | Costs | 4.21% | 13.35 |
| 9 | Scaled estimate of annual number of incidents *line 2 / line 7 multiplier* | | 26.80 |
| 10 | Scaled total annual recovery cost ($/sq.ft) *line 3 × $1M / line 8 / line 9 / line 6* | | 3.58 |

| Bridge susceptibility | |
|---|---|
| Flood impingement on bridge *(field assessment)* | |
| Under superstructure | 0.1 |
| Water pressure on superstructure | 0.3 |
| Water over approach | 0.5 |
| Water over bridge deck | 0.8 |
| Severe scour | 0.5 |
| Mitigation effectiveness *(to be assessed in the field)* | |
| High | 0.3 |
| Medium | 0.5 |
| Low | 1 |

### *Worksheet LD-Flood*

In flood-prone areas, agencies typically have enough information or experience with flood damage to enable the use of the risk allocation method.

Although inspectors are required to gather NBI item 71, waterway adequacy, this data item has limited ability to inform risk mitigation decision making. By combining the concerns of extreme event likelihood, structure impingement, service disruption severity, duration of consequences, and functional classification, it does not provide a clear measure of any of these characteristics individually.

It is far better if the inspector is informed in advance, by the geographic analysis, of the situation of the bridge (location and elevation) with respect to the 100-year flood zone, or other recurrence interval identified in the hazard scenario. Then the inspector makes the flood damage likelihood assessment with that specific scenario in mind. The inspector should at least classify how the flood water level would likely relate to the bridge deck and approach, and should also assess the effectiveness of any mitigation features present. The lower part of the worksheet at left gives an example.

With this information, the calculations described in Section 3.4.1.5 above can give a very useful estimate of the likelihood of service disruption.

Flood behavior often involves scour, and the damage is influenced by the extent and severity of previous scour at the site. As a result, agencies may want to consider combining the flood and scour assessments.

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**Sheet LD - Scour 1**

| | | |
|---|---|---|
| Hazard scenario | **Scour1** | |
| Area considered | **Statewide** | |

| Summary of historical analysis and polling | | |
|---|---|---|
| 1 | Number of years covered (T) | 20 |
| 2 | Estimated total number of bridges affected over this period | 500 |
| 3 | Estimated total expenditure on incident recovery ($ million) | 15.3 |

| Scaling | | | |
|---|---|---|---|
| | | Starting | Ending |
| 4 | Construction cost index | 5744 | 10092 |
| 5 | Number of bridges | 10,500 | 12,000 |
| 6 | Average deck area (sq.ft) | 10,540 | 11,965 |
| | | Growth rate | Multiplier |
| 7 | Number of incidents | 0.67% | 18.66 |
| 8 | Costs | 4.21% | 13.35 |
| 9 | Scaled estimate of annual number of incidents *line 2 / line 7 multiplier* | | 26.80 |
| 10 | Scaled total annual recovery cost ($/sq.ft) *line 3 × $1M / line 8 / line 9 / line 6* | | 3.58 |

*Table 3. Scoring table for scour (adapted from Minnesota DOT, Thompson et al 2012)*

| Bridge scour susceptibility | | | | | |
|---|---|---|---|---|---|
| | | Defect reduction | | | |
| Code | Description | None | 2 | 3 | 4 |
| A | Not a waterway | 100 | 100 | 100 | 100 |
| E | Culvert | 100 | 100 | 100 | 100 |
| M | Stable; scour above footing | 90 | 90 | 70 | 40 |
| H | Foundation above water | 90 | 90 | 70 | 40 |
| N | Stable; scour in footing/pile | 80 | 80 | 60 | 30 |
| I | Screened; low risk | 70 | 70 | 50 | 30 |
| L | Evaluated; stable | 70 | 70 | 50 | 30 |
| P | Stable due to protection | 60 | 60 | 40 | 20 |
| K | Screened; limited risk | 60 | 60 | 30 | 20 |
| F | No eval; foundation known | 50 | 50 | 40 | 20 |
| C | Closed; no scour | 50 | 50 | 25 | 20 |
| J | Screened; susceptible | 40 | 40 | 30 | 10 |
| O | Stable; action required | 40 | 40 | 20 | 10 |
| G | No eval; foundation unknown | 20 | 20 | 15 | 10 |
| R | Critical; monitor | 10 | 10 | 5 | 0 |
| B | Closed; scour | 0 | 0 | 0 | 0 |
| D | Imminent protection reqd | 0 | 0 | 0 | 0 |
| U | Critical; protection required | 0 | 0 | 0 | 0 |
| Smart flag reduction: | | | | | |
| Use worst condition state of defect 6000, Scour | | | | | |

### *Worksheet LD-Scour*

Various agencies have developed scour risk assessment procedures, tailored to their own needs. These Guidelines present two examples of published work where the likelihood of service disruption can be estimated. There is room for further innovation in this area, for agencies wishing to research the issue.

**Minnesota** DOT has developed a field assessment for scour, which can be used in combination with the risk allocation method to estimate likelihood of service disruption (Table 3, Thompson et al 2012). The field assessment is somewhat more detailed than what is in the National Bridge Inventory, and, at the time of its development, relied on the AASHTO Guide for Commonly-Recognized (CoRe) Structural Elements for the Scour smart flag (AASHTO 1998). Here it is adapted to use the new Scour Defect element defined in the AASHTO Manual for Bridge Element Inspection (AASHTO 2013).

With a field assessment performed as in Table 3, agencies can apply the risk allocation computations described in Section 3.4.1.5, using the Scour 1 worksheet at left, to estimate likelihood of service disruption on each bridge. Under the recommended methodology, scour (in contrast to flooding) does not have an extreme event likelihood, so the full probability of service disruption is based on the scour assessment made in the field.

If agencies wish to use a Defect element in this assessment, it is important to note that the AASHTO manual suggests that inspectors code only the worst defect affecting the condition state of each element. If agencies follow this guidance, it is possible that Scour defects might not be coded consistently. For example, if substructure elements experience spalling in condition state 3, then scour in condition state 2 might not be recorded. Agencies wishing to use the Scour defect for risk analysis should therefore instruct inspectors to always record the Scour defect, if applicable, regardless of the presence of other defects on substructure elements.

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**Sheet LD - Scour 2**

| | | |
|---|---|---|
| Bridge ID | **010001** | |
| Hazard scenario | **Scour2** | |

| Likelihood of service disruption | | |
|---|---|---|
| 1 | Functional class | 14 - Urban other principal arterial |
| 2 | Waterway adequacy (NBI 71) | 3 |
| 3 | Overtopping frequency *(Table 4)* | O |
| 4 | Channel/protection condition (NBI 61) | 5 |
| 5 | Substructure condition (NBI 60) | 6 |
| 6 | Scour susceptibility *(Table 5)* | 5 |
| 7 | Likelihood of service disruption *(Table 6)* | **0.050 00 %** |

**Georgia** DOT, unlike Minnesota, considers scour and flooding together in one assessment for risk analysis (Garrow and Sturm 2013). The method is based on NCHRP research (Stein and Sedmera 2006) with minor modifications. The earlier work had used the HYRISK model to simulate a variety of scenarios, to try to estimate the probability of failure due to scour or flood. In that study, "failure" referred to structural failure such that the change in geometry rendered the road impassable. This is a somewhat narrower definition than "service disruption," because an agency may decide operationally to temporarily restrict access to a bridge that is experiencing scour or flooding even if there has not yet been a change in geometry. Usually such actions are short in duration, in comparison to the loss of service if the bridge does undergo structural failure. It may be justifiable, therefore to ignore the difference in definitions of the hazard scenario.

In the NCHRP research, the initial runs of the HYRISK model produced failure probabilities that were significantly higher than actual bridge failure experience. To compensate, the researchers applied the risk allocation method, using a national database of bridges, to scale the modeled probabilities so the total predicted number of failures agreed with an estimate of the actual number of failures of bridges in the same database. As a result, agencies wishing to use the method do not have to perform an additional risk allocation, but can read the failure probability directly from the research results tables. This makes the method very convenient.

To apply the method, use the Scour 2 worksheet at left. Obtain the overtopping frequency from Table 4 and the classification of scour susceptibility from Table 5. Then use these values to look up the annual disruption likelihood from Table 6. This model does not have a separate extreme event likelihood, so the resulting probabilities are smaller than the results of the earlier natural hazard models.

Agencies wishing to apply the Georgia method may wish to perform a quality assurance review of NBI items 60, 61, and 71 in their inspection procedures and systems, to ensure that the level of quality is appropriate for this risk analysis, particularly if these data items were not previously used for project development and priority-setting decisions.

*Table 4. Estimation of overtopping frequency for Scour 2*

| Overtopping frequency | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Waterway adequacy (NBI 71) | | | | | | | | | | |
| Functional class (NBI 26) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | N |
| Principal Arterials – Interstates (01,11) | C | C | O | O | O | O | S | S | S | R | N |
| Freeways or Expressways (12) | C | C | F | O | O | O | S | S | S | R | N |
| Other principal arterials (02, 14) | C | C | F | O | O | O | S | S | S | R | N |
| Minor arterials (06,16) | C | C | F | O | O | O | S | S | S | R | N |
| Major Collectors (07,17) | C | C | F | O | O | O | S | S | S | R | N |
| Minor Arterials (08) | C | C | F | F | O | O | O | S | S | R | N |
| Locals (09,19) | C | C | F | F | O | O | O | S | S | R | N |

| Legend | Probability | Return (yrs) |
|---|---|---|
| C - Bridge closed | N/A | N/A |
| N - None | 0 | Never |
| R - Remote | 0.01 | > 100 |
| S - Slight | 0.02 | 11 to 100 |
| O - Occasional | 0.2 | 3 to 10 |
| F - Frequent | 0.3 | < 3 |

*Table 5. Classification of scour susceptibility for Scour 2*

| Scour susceptibility | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Substructure condition (NBI 60) | | | | | | | | | | |
| Channel condition (NBI 61) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | N |
| 0 - Failure | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 - Failure | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | N |
| 2 - Near collapse | 0 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | N |
| 3 - Channel migration | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | N |
| 4 - Undetermined bank | 0 | 1 | 2 | 3 | 4 | 4 | 5 | 5 | 6 | 6 | N |
| 5 - Eroded bank | 0 | 1 | 2 | 3 | 4 | 5 | 5 | 6 | 7 | 7 | N |
| 6 - Bed movement | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 6 | 7 | 7 | N |
| 7 - Minor drift | 0 | 1 | 2 | 3 | 4 | 6 | 6 | 7 | 7 | 8 | N |
| 8 - Stable condition | 0 | 1 | 2 | 3 | 4 | 6 | 7 | 7 | 8 | 8 | N |
| 9 - No deficiencies | 0 | 1 | 2 | 3 | 4 | 7 | 7 | 8 | 8 | 9 | N |
| N - Not over water | 0 | 1 | N | N | N | N | N | N | N | N | N |

*Table 6. Estimation of likelihood of service disruption for Scour 2*

| Likelihood of service disruption | | | | |
|---|---|---|---|---|
| | Overtopping frequency *(from Table 4)* | | | |
| Scour susceptibility | R - Remote | S - Slight | O - Occasional | F - Frequent |
| *(from Table 5)* | 0.01 | 0.02 | 0.2 | 0.3 |
| 0 - Failed | 100.000 00 % | 100.000 00 % | 100.000 00 % | 100.000 00 % |
| 1 - Imminent failure | 1.000 00 % | 1.000 00 % | 1.000 00 % | 1.000 00 % |
| 2 - Critical scour | 0.500 00 % | 0.600 00 % | 0.800 00 % | 0.900 00 % |
| 3 - Serious scour | 0.110 00 % | 0.130 00 % | 0.160 00 % | 0.200 00 % |
| 4 - Advanced scour | 0.040 00 % | 0.050 00 % | 0.060 00 % | 0.070 00 % |
| 5 - Minor scour | 0.030 00 % | 0.040 00 % | 0.050 00 % | 0.070 00 % |
| 6 - Minor deterioration | 0.018 00 % | 0.025 00 % | 0.040 00 % | 0.050 00 % |
| 7 - Good condition | 0.018 00 % | 0.025 00 % | 0.040 00 % | 0.050 00 % |
| 8 - Very good condition | 0.000 40 % | 0.000 50 % | 0.002 00 % | 0.004 00 % |
| 9 - Excellent condition | 0.000 25 % | 0.000 30 % | 0.000 40 % | 0.000 70 % |

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**Sheet LD - Wildfire**

| | | |
|---|---|---|
| Hazard scenario | **Wildfire-100** | |
| Area considered | **Statewide** | |

| Summary of historical analysis and polling | | |
|---|---|---|
| 1 | Number of years covered (T) | 20 |
| 2 | Estimated total number of bridges affected over this period | 500 |
| 3 | Estimated total expenditure on incident recovery ($ million) | 15.3 |

| Scaling | | | |
|---|---|---|---|
| | | Starting | Ending |
| 4 | Construction cost index | 5744 | 10092 |
| 5 | Number of bridges | 10,500 | 12,000 |
| 6 | Average deck area (sq.ft) | 10,540 | 11,965 |
| | | Growth rate | Multiplier |
| 7 | Number of incidents | 0.67% | 18.66 |
| 8 | Costs | 4.21% | 13.35 |
| 9 | Scaled estimate of annual number of incidents *line 2 / line 7 multiplier* | | 26.80 |
| 10 | Scaled total annual recovery cost ($/sq.ft) *line 3 × $1M / line 8 / line 9 / line 6* | | 3.58 |

| Bridge susceptibility | |
|---|---|
| Material *(NBI 43 and 44)* | |
| Concrete, other | 0.2 |
| Steel, iron | 1 |
| Timber | 2 |
| Fuel availability *(to be assessed in the field)* | |
| Low | 0.2 |
| Medium | 1 |
| High | 2 |
| Mitigation effectiveness *(to be assessed in the field)* | |
| High | 0.5 |
| Medium | 1 |
| Low | 1.5 |

### *Worksheet LD-Wildfire*

Wildfire was used earlier in Section 3.4.1.5 as an example use of the risk allocation method. To fill out the worksheet at left, it is necessary to generate an estimate, over a long period of time of the number of instances where a wildfire has disrupted transportation service on a bridge. This may require a search through news media archives unless districts have kept records of these incidents. Polling of district maintenance personnel is another way to supplement or replace a news search.

In addition to likelihood, the worksheet also addresses recovery cost. It is possible, however, to use the worksheet just for estimating likelihood, and use a different method (such as agency programmatic estimation procedures) to develop a recovery cost estimate separately. In the worksheet, lines 1, 2, 5, 7, and 9 are all that is needed for the likelihood estimate.

Different bridges will have different values of the likelihood of service disruption, depending on potentially many factors. The bottom portion of the worksheet suggests one way of assessing the relative likelihood in the field. There is no standardized assessment procedure for wildfires, so the agency should feel free to design the assessment in a way that reflects its typical experiences with this hazard.

What is important in these susceptibility factors is the relative probabilities among the categories. For example, the Material table estimates that timber structures are twice as likely to be damaged as steel structures. These are established from judgment. The absolute magnitudes of these factors are not important since they will be scaled in a later step to agree with historical incident frequencies.

In the scaling step discussed in Section 3.4.1.5 and shown by example in Table 2 above, it is assumed that an extreme event likelihood has been developed using a geographic analysis. Not all states have data that can be used for this. In the absence of such data, the worksheet can still be used, but in this case treat the extreme event likelihood as 1.0. This will have the effect of including it within the service disruption likelihood estimate.

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## Sheet LD - Temperature

| | |
|---|---|
| Hazard scenario | **Temperature** |
| Area considered | **Statewide** |

**Summary of historical analysis and polling**

| | | |
|---|---|---|
| 1 | Number of years covered (T) | 20 |
| 2 | Estimated total number of bridges affected over this period | 500 |
| 3 | Estimated total expenditure on incident recovery ($ million) | 15.3 |

**Scaling**

| | | Starting | Ending |
|---|---|---|---|
| 4 | Construction cost index | 5744 | 10092 |
| 5 | Number of bridges | 10,500 | 12,000 |
| 6 | Average deck area (sq.ft) | 10,540 | 11,965 |
| | | Growth rate | Multiplier |
| 7 | Number of incidents | 0.67% | 18.66 |
| 8 | Costs | 4.21% | 13.35 |
| 9 | Scaled estimate of annual number of incidents *line 2 / line 7 multiplier* | | 26.80 |
| 10 | Scaled total annual recovery cost ($/sq.ft) *line 3 × $1M / line 8 / line 9 / line 6* | | 3.58 |

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## Sheet LD - Temperature

| | |
|---|---|
| Bridge ID | **010001** |
| Hazard scenario | **Temperature** |

**Likelihood of service disruption**

| Range | Probability | Use value | Check one |
|---|---|---|---|
| None | < 5 | 0 | ○ |
| Low | < 35 | 25 | ○ |
| Moderate | < 65 | 50 | ○ |
| High | < 95 | 75 | ○ |
| Certain | >= 95 | 100 | ○ |

Specific probability (optional)

### *Worksheet LD-Temperature extremes*

If an agency is experiencing incidents where bridges are damaged by extreme temperature events, the worksheets at left may be appropriate. The upper worksheet is used at the network level to develop an estimate of service disruption likelihood and recovery cost. This can be used with or without an estimate of extreme event likelihood, in the same manner as discussed with the Wildfire worksheet.

The lower worksheet would be used by bridge inspectors with the AASHTOWare Bridge Management Assessment feature, to enable inspectors to classify structures where damage from extreme temperatures is possible. Instructions and training would need to be provided for inspectors to perform the assessment in a consistent manner. Potential considerations are:

- Bearing displacement
- Expansion joint debris impaction
- Joint clearance in proportion to span length
- Evidence of joint contact
- Evidence of deck or railing displacement
- Cracking in girders, deck, parapet, or railing

Section 3.4.1.5 provides more information on how to use the assessment results within the risk allocation procedure.

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## Sheet LD - Permafrost

| | |
|---|---|
| Hazard scenario | **Permafrost-100** |
| District | **2** |
| Respondent | **IM456** |

**Recollection of past incidents**

Please jog your memory and list as many incidents as you can when permafrost instability damaged a bridge or otherwise forced a bridge closure or delay

| ID | Bridge | Year | Duration (days) | Impact |
|---|---|---|---|---|
| 1 | 010001 | 2014 | 30 | Destroyed |
| 2 | 157892 | 2012 | 1 | Closure |
| 3 | 150087 | 2009 | 45 | Destroyed |
| 4 | 226543 | 2009 | 14 | Damaged |
| 5 | 220007 | 2007 | 2 | Closure |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |

**Scaling**

| | | |
|---|---|---|
| 11 | How many years back can you reliably remember these incidents? | 10 |
| 12 | How many additional incidents do you believe occurred during this period? | 5 |
| 13 | Total number of bridges affected | 10 |
| 14 | Number of bridges in permafrost-vulnerable areas in the district | 1120 |
| 15 | Permafrost instability failure probability *(GIS analysis)* | 0.540% |
| 16 | Likelihood of service disruption *(Line 13 ÷ Line14 ÷ Line 11 ÷ Line 15)* | **16.534%** |

### *Worksheet LD-Permafrost instability*

Agencies that experience permafrost instability may wish to use the polling worksheet, at left, to gather incident data and estimate service disruption probabilities. The procedure is similar to landslides, but may produce different probabilities and affect a different population of bridges. The types of bridge distress that might be considered include settlement, approach embankment instability, and lateral pressure on substructure units from debris flow or ice.

Agencies having extensive permafrost areas would be likely to have GIS maps of these areas. However, the maps might not provide enough information to produce extreme event probabilities. In this case, treat line 15 in the worksheet as 1.0, and then the entire incident probability will be included within the estimate of likelihood of service disruption.

Risk allocation can be used in combination with the polling method if the agency wishes to perform a field assessment of permafrost-related problems. This would enable bridge characteristics to influence the final determination of likelihood of service disruption.

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**Sheet LD - Overload**

| | | |
|---|---|---|
| 1 | Bridge ID | **010001** |
| 2 | Forecast year | **2018** |
| 3 | Hazard scenario | **Overload** |
| | **Truck volume prediction** | |
| 4 | Functional class | 14 - Urban other principal arterial |
| 5 | Average daily traffic (NBI 29) | 23,000 |
| 6 | Year of average daily traffic (NBI 30) | 2010 |
| 7 | Future average daily traffic (NBI 114) | 29,000 |
| 8 | Year of future average daily traffic (NBI 115) | 2030 |
| 9 | Growth rate<br>*(line 7 / line 5) ^(1 / (line 8 -line 6)) - 1* | 1.17% |
| 10 | Truck percent (NBI 109) | 5.50% |
| 11 | Projected average daily truck traffic<br>*line 5 × (1+line 9) ^(line 2-line 6) × line 10* | 1,388 |
| | **Number of overweight trucks** | |
| 12 | Operating rating (NBI 64, pounds) | 64,000 |
| 13 | Percent of trucks exceeding op rating<br>*(compute from truck histogram)* | 13.47% |
| 14 | Annual trucks exceeding<br>*365 × line 11 × line 13* | **68,245** |

*Worksheet LD-Overload*

The Florida Department of Transportation developed a model of truck weights in the traffic stream, based on data gathered on weigh-in-motion equipment located at strategic places on the state highway network (Sobanjo and Thompson 2004). With this information and the operating rating of a given bridge, it is possible to compute the number of trucks each year that are (in principle) unable to use the bridge, using the worksheet at left.

In the Florida model, the fraction of trucks detoured is:

For bridges carrying interstate highways:

| | |
|---|---|
| OR<10000 | 100 |
| OR<80000 | 102.24 - (8.982E-5)*OR - (1.4336E-8)*OR^2 |
| OR<91000 | 18.976 - (2.083E-4)*OR |
| OR higher | 0 |

(11)

For all other functional classes:

| | |
|---|---|
| OR<3725 | 100 |
| OR<85000 | 107.26 - (1.9743E-3)*OR + (6.5265E-9)*OR^2 + (2.2256E-14)*OR^3 |
| OR higher | 0 |

Where OR is the operating rating of the bridge, in pounds (NBI item 64).

Of the trucks that exceed the operating rating, there is an unknown probability that passage over the bridge will cause damage sufficient to disrupt service. In the absence of specific information about this unknown probability, the risk allocation method, possibly in combination with the polling method, can be used to estimate it. The likelihood of service disruption will then be proportional to the number of trucks exceeding the operating rating.

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**Sheet LD - Over-height**

| | | |
|---|---|---|
| 1 | Bridge ID | **010001** |
| 2 | Forecast year | **2018** |
| 3 | Hazard scenario | **Over-height** |
| | **Truck volume prediction** | |
| 4 | Functional class | 14 - Urban other principal arterial |
| 5 | Average daily traffic (NBI 29) | 23,000 |
| 6 | Year of average daily traffic (NBI 30) | 2010 |
| 7 | Future average daily traffic (NBI 114) | 29,000 |
| 8 | Year of future average daily traffic (NBI 115) | 2030 |
| 9 | Growth rate<br>*(line 7 / line 5) ^(1 / (line 8 - line 6)) - 1* | 1.17% |
| 10 | Truck percent (NBI 109) | 5.50% |
| 11 | Projected average daily truck traffic<br>*line 5 × (1+line 9) ^(line 2-line 6) × line 10* | 1,388 |
| | **Trucks exceeding the vertical clearance** | |
| 12 | Vertical clearance in feet (NBI 10) | 13.50 |
| 13 | Percent of trucks exceeding clearance<br>*(compute from truck histogram)* | 5.40% |
| 14 | Annual trucks exceeding<br>*365 × line 11 × line 13* | **27,350** |

### *Worksheet LD-Over-height collision*

The Florida Department of Transportation developed a model of truck heights in the traffic stream, based on data gathered using portable laser range-finding equipment located at strategic places on the state highway network (Sobanjo and Thompson 2004). With this information and the vertical clearance over a given bridge roadway, it is possible to compute the number of trucks each year that are (in principle) unable to pass under or through the bridge, using the worksheet at left.

In the Florida model, the fraction of trucks detoured is:

For bridges carrying interstate highways:

| | | |
|---|---|---|
| VC<9.65 | 100 | |
| VC<13 | 855.91 - 223.43*VC + 22.199*VC^2 - 0.74236*VC^3 | |
| VC<14 | (1.0956E+56)*VC^(-48.683) | (12) |
| VC<16.1 | 14.567 - 0.9046*VC | |
| VC higher | 0 | |

For all other functional classes:

| | |
|---|---|
| VC<7.3 | 100 |
| VC<13.5 | -26.275 + 34.692*VC - 2.3894*VC^2 |
| VC<14 | 138.86 - 9.886*VC |
| VC higher | 0 |

Where VC is the vertical clearance over the roadway, in feet (NBI item 10). This can apply to roadways under a bridge or on it, if vertical clearance is restricted.

Of the trucks that exceed the vertical clearance, there is an unknown probability that a collision with the bridge will cause damage sufficient to disrupt service. In the absence of specific information about this unknown probability, the risk allocation method, possibly in combination with the polling method, can be used to estimate it. The likelihood of service disruption will then be proportional to the total number of trucks exceeding the vertical clearance on and under the bridge.

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**Sheet LD - Truck collision**

| | | |
|---|---|---|
| 1 | Bridge ID | **010001** |
| 2 | Forecast year | **2018** |
| 3 | Hazard scenario | **Truck collision** |

**Traffic volume prediction**

| | | |
|---|---|---|
| 4 | Functional class | 14 - Urban other principal arterial |
| 5 | Average daily traffic (NBI 29) | 23,000 |
| 6 | Year of average daily traffic (NBI 30) | 2010 |
| 7 | Future average daily traffic (NBI 114) | 29,000 |
| 8 | Year of future average daily traffic (NBI 115) | 2030 |
| 9 | Growth rate<br>*(line 7 / line 5) ^(1 / (line 8 - line 6)) - 1* | 1.17% |
| 10 | Truck percent (NBI 109) | 5.50% |
| 11 | Projected average daily traffic<br>*line 5 × (1+line 9) ^(line 2-line 6)* | 25,235 |

**Probability of truck crashes**

| | | | |
|---|---|---|---|
| 12 | Term 1 (urban arterials)<br>*886.0 if urban arterial, -377.4 otherwise* | | 886.0 |
| 13 | Number of lanes (NBI 28) | | 4 |
| 14 | Bridge length in feet (NBI 49 or 52)<br>*(use 49 for roadway-on, and 52 for under)* | | 540 |
| 15 | Term 2 (lanes × length)<br>*0.2232 × line 13 × line 14* | | 482.1 |
| 16 | Approach alignment (NBI 72) | | 7 |
| 17 | Deck condition (NBI 58) | | 5 |
| 18 | Coef3 (approach and deck) | | 1.4866 |
| | *Approach <= 6 and deck <=6* | *2.5917* | |
| | *Approach<=6 and deck > 6* | *1.6507* | |
| | *Approach > 6 and deck <=6* | *1.4866* | |
| | *Approach > 6 and deck > 6* | *1.2809* | |
| 19 | Roadway width in feet (NBI 51) | | 88 |
| 20 | Term 3 (narrowness × adt)<br>*line 18 × line 13 / line 19 × line 11* | | 1705.2 |
| 21 | Predicted annual truck accidents<br>*line 10 × (line 12 + line 15 + line 20) / 1000* | | **0.1690** |

*Worksheet LD-Truck collision*

The Florida Department of Transportation developed a model of accident risk based on an analysis of statewide crash data and bridge characteristics (Thompson et al 1999). It found that narrow lanes, approach alignment, and deck condition contributed significantly to higher accident rates. The worksheet at right uses this model to predict the annual number of crashes involving trucks at a bridge site. Improvements to a bridge that improve its roadway width, approach alignment, or deck condition have the effect of improving the predicted accident count.

Of the truck-involved accidents, there is an unknown probability that the crash will damage the bridge to a sufficient extent to cause an extended disruption in service. One approach is to treat all truck crashes as interrupting service, and recognize the typical truck crash recovery time as a consequence. Another approach is to recognize only those crashes that damage a bridge and require a longer period of time to repair the damage and open the bridge for service. The probability of this less frequent scenario is unknown, but can be estimated using risk allocation, possibly combined with polling.

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**Sheet LD - Vessel collision**

| | |
|---|---|
| Hazard scenario | **Vessel collision** |
| District | **2** |
| Respondent | **IM456** |

Recollection of past incidents

Please jog your memory and list as many incidents as you can when a vessel collision damaged a bridge or otherwise forced a bridge closure or delay

| ID | Bridge | Year | Duration (days) | Impact |
|---|---|---|---|---|
| 1 | 010001 | 2014 | 30 | Destroyed |
| 2 | 157892 | 2012 | 1 | Closure |
| 3 | 150087 | 2009 | 45 | Destroyed |
| 4 | 226543 | 2009 | 14 | Damaged |
| 5 | 220007 | 2007 | 2 | Closure |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |

Scaling

| | | |
|---|---|---|
| 11 | How many years back can you reliably remember these incidents? | 10 |
| 12 | How many additional incidents do you believe occurred during this period? | 5 |
| 13 | Total number of bridges affected | 10 |
| 14 | Number of bridges in district *(from BMS)* | 1120 |
| 15 | Likelihood of service disruption *(Line 13 ÷ Line14 ÷ Line 11)* | **0.089%** |

*Worksheet LD-Vessel collision*

Unless the agency maintains a source of bridge collision reports, estimation of vessel collision risk can be accomplished using the polling method and risk allocation. Only bridges on navigable waters, with substructures in the water, would be considered. Navigable waterways can be identified in a BMS, but the location of substructures would need to be established on-site.

Vessel collisions include collisions with bridge protective systems such as fenders and dolphins. The probability of service disruption therefore depends strongly on the effectiveness of the protective systems as well as the volume of ship traffic. If vessel collision is a significant concern on a large number of bridges, a field assessment of these variables may be warranted.

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**Sheet LD - Terrorism**

Bridge ID **010001**

Hazard scenario **FI-100a**

Answer the questions below for each bridge using field data or NBI data.

| | Questions Related to the Occurrence Factor | Answer | Weight | Score |
|---|---|---|---|---|
| 1 | Is there sufficient lighting on the superstructure? | Yes | 0.1613 | 0.0000 |
| 2 | Is there enough space around the bearings to place a 6"x6"x6" object? | Yes | 0.0951 | 0.0951 |
| 3 | Can someone park under/on bridge? | Yes | 0.1720 | 0.1720 |
| 4 | Is there a shoulder on the bridge? | Yes | 0.0714 | 0.0714 |
| 5 | Is there a sidewalk or a pedestrian walkway? | Yes | 0.0605 | 0.0605 |
| 6 | Is there easy access to the deck from underneath the bridge? | Yes | 0.0923 | 0.0923 |
| 7 | Is there an access to the bearings? | Yes | 0.0856 | 0.0856 |
| 8 | Is there easy access to the pile cap? | Yes | 0.0654 | 0.0654 |
| 9 | Is there easy access to the abutment and/or the wingwalls? | Yes | 0.0450 | 0.0450 |
| 10 | Are pipelines located under/over bridge? | Yes | 0.0419 | 0.0419 |
| 11 | Are gas pipes located under/over bridge? | Yes | 0.0775 | 0.0775 |
| 12 | Are power lines located under/over bridge? | No | 0.0320 | 0.0000 |
| | | Total | **1.00** | **0.81** |

| | Questions Related to the Vulnerability Factor | Answer | Weight | Score |
|---|---|---|---|---|
| 1 | Are the bearings securely anchored in place? | Yes | 0.1278 | 0.0000 |
| 2 | Is the pier/tower a single column, two-column, three-column or more than 3? | single | 0.1784 | 0.1784 |
| 3 | Do the pier columns have sufficient confinement? | No | 0.1776 | 0.1776 |
| 15 | Does roadway drain to beneath bridge?(gasoline fire under bridge from truck accident) | Yes | 0.1046 | 0.1046 |
| 16 | storage of vehicles under bridge or excessive garbage accumulation) | No | 0.1324 | 0.0000 |
| 17 | Is there a secure perimeter or zone around the bridge? Around certain bridge components? | No | 0.1231 | 0.1231 |
| 18 | What is the bridge sufficiency rating? | 90 | 0.0655 | 0.0000 |
| 19 | Is there a protection around the pier/tower? | No | 0.0906 | 0.0906 |
| | | Total | **1.00** | **0.67** |

| | Questions Related to the Importance Factor | Answer | Weight | Score |
|---|---|---|---|---|
| 1 | Is the bridge near or on route to high value target? | Yes | 0.3624 | 0.3624 |
| 2 | Is the bridge over or near chemical/refinery/industrial | No | 0.2443 | 0.0000 |
| 3 | What is the length of the longest span in feet? | 3500 | 0.1250 | 0.1250 |
| 4 | What is the annual average daily traffic of the bridge? | 296900 | 0.1459 | 0.1459 |
| 5 | Is the bridge part of a Coastal Evacuation Route? | No | 0.1225 | 0.0000 |
| 6 | Is the bridge culturally or historically significant? i.e. Is this structure a well known landmark? | Yes | 1.0000 | 1.0000 |
| | | Total | **1.00** | **1.00** |

**Risk = O * V * I = 0.54**

*Worksheet LD-Terrorism/Countering Violent Extremism*

A Simple Bridge Security checklist was created by Rutgers University in 2002 and then updated in 2010 (Valeo, 2010) to include weights calculated using the Analytic Hierarchy Process to improve functionality.

The information required to complete the simple checklist is easily available from inspection data and the NBI. This can be done for all bridges, or for a smaller sampling of bridges. The user would answer the questions (many are yes/no) and a value of overall risk, between 0 and 1 would be computed. The closer the value is to 1, the higher the risk for the structure would be.

The weights within the checklist have been calibrated using the Analytic Hierarchy Process, and have been tested on several projects in the state of NJ. These weights could be adjusted based on an owners' judgement to meet their state specific needs.

| NCHRP 20-07 (378) Risk Analysis<br>**Sheet LD - Advanced deterioration** | | | | |
|---|---|---|---|---|
| 1 | Bridge ID | **910081** | | |
| 2 | Forecast year | **2018** | | |
| 3 | Hazard scenario | **Deterioration** | | |

| Decay index and likelihood of service disruption | | | | |
|---|---|---|---|---|
| 4 | Decay index (DI) based on element conditions<br>*(computations in Table 5)* | | | 19.44 |
| 5 | Main unit material (NBI 43A) | | | Concrete - prestressed |
| 6 | Model mean | | | 15.461 |
| 7 | Model standard deviation | | | 3.982 |
| | | Mean | StdDev | |
| | Concrete - prestressed | 15.461 | 3.982 | |
| | Concrete - reinforced | 15.385 | 3.928 | |
| | Steel | 15.545 | 3.998 | |
| | Timber | 15.077 | 3.902 | |
| 8 | Decay status (number of standard deviations)<br>*( ln (line 4) - line 6) / line 7* | | | -3.1375 |
| 9 | Probability density function (PDF) | | | 0.000730 |
| 10 | Cumulative probability (CDF) | | | 0.000852 |
| 11 | Hazard function value<br>3000 × *line 9 / (line 7 × line 4 × (1-line 10))* | | | 0.02831 |
| 12 | Delay coefficient (Dcoef) | | | 0.00199 |
| | Concrete - prestressed | 0.00199 | | |
| | Concrete - reinforced | 0.00047 | | |
| | Steel | 0.00196 | | |
| | Timber | 0.00539 | | |
| 13 | Likelihood of service disruption<br>*line 11 + line 12 × line 4* | | | **6.70%** |

### *Worksheet LD-Deterioration*

The Florida Department of Transportation developed a model of the likelihood of service disruption caused by advanced deterioration (Sobanjo and Thompson 2013). The disruption in this case is the need to load-post, reconstruct, or replace the bridge prematurely. To develop this model, the Department used 14 years of data on 15,548 active and retired bridges, and performed an analysis of the reasons for 1,480 bridge replacements in order to isolate the 327 bridges that were replaced primarily because of deterioration, and 440 more where deterioration may have contributed to the justification. Bridges on and off the state highway system were included.

Since this type of analysis had not been performed for bridges before, several explanatory theories were developed and tested using statistical models. The final selection was a lognormal model very commonly used for financial risk analysis and mechanical failure models. The analysis has two steps:

1. A modified health index (Shepard and Johnson 2001), called the decay index, was developed. It considers only primary load-bearing structural elements, and focuses on the worst and second-worst condition states defined for each element.
2. A regression model was developed to relate the decay index to the likelihood of service disruption. This is called a lognormal model because the natural log of the decay index is located within a standard normal distribution.

The decay index in Step 1 is computed from element-level data using the methods and tables presented below. It is then entered as line 4 in the worksheet at left, where the Step 2 computations are performed.

**Decay index.** Analysis of posting, reconstruction, and replacement projects found that condition-related service disruptions were associated with the percent of primary elements in the worst defined condition state and (to a lesser extent) in the second-worst state. A regression analysis was performed to quantify the extent of this influence. The resulting decay index is computed from current or forecast element-level condition as follows:

$$DI = 100 \times \sum_{c} \frac{W_c}{TEV_c} \left( \sum_{s} w_{cs} CEV_{cs} \right)$$

$$CEV_{cs} = \sum_{e \in c} (P_{es} Q_e C_e) \tag{13}$$

$$TEV_c = \sum_{e \in c} (Q_e C_e)$$

Where $P_{es}$ = Fraction of element $e$ observed or forecast to be in condition state $s$
$Q_e$ = Quantity of element $e$ on the bridge
$C_e$ = Unit replacement cost of element $e$
$W_c$ = Relative weight (importance) of component c (Table 7)
$w_{cs}$ = Relative weight (importance) of condition state $s$ of component $c$ (Table 7)

The condition state weight $w_{cs}$ is 1.0 for the worst-defined condition state of each element, and is tabulated in Table 7 for the second-worst state. It is zero for all other states. Table 8 shows an example data set in the upper portion, and the component-level calculations in the lower portion.

*Table 7. Decay index weights*

| | Component weight | | | Weight for state 3 | | |
|---|---|---|---|---|---|---|
| Material | Deck | Super | Sub | Deck | Super | Sub |
| Concrete -prestress | 20% | 40% | 40% | 50% | 50% | 50% |
| Concrete -reinforced | 20% | 40% | 40% | 50% | 50% | 50% |
| Steel | 20% | 40% | 40% | 50% | 50% | 50% |
| Timber | 40% | 40% | 20% | 10% | 50% | 50% |

**Probability.** Analysis of the data set produced a probability distribution of the natural log of decay index, which provides a normalized indication of how far a bridge is within the progression over time of the worst condition states. Line 7 in the worksheet shows the mean and standard deviation (StdDev) of the distribution, which varies slightly by material type (based on NBI item 43A). On this probability distribution, the current location of the bridge is described by line 8, which is expressed in terms of the number of standard deviations before or after the mean.

From this information, a regression model estimates the likelihood of service disruption as follows:

$$LD_b = \frac{3000 \times PDF}{StdDev \times DI \times (1 - CDF)} + Dcoef \times DI \qquad (14)$$

Where $DI$ = Decay index (result of Table 8)
$PDF$ = Probability density function
$CDF$ = Cumulative density function
$StdDev$ =Standard deviation (worksheet line 7)
$Dcoef$ =Delay coefficient (worksheet line 12)

The PDF and CDF are both computed using the natural log of DI on a probability distribution whose mean is worksheet line 6 and whose standard deviation is worksheet line 7. In an Excel spreadsheet, these are easily computed using the following functions:

PDF=NORMDIST(ln(DI),Mean,StdDev,FALSE)
CDF=NORMDIST(ln(DI),Mean,StdDev,TRUE)

For other computational platforms, library functions or standard statistical texts should be consulted for appropriate methods, including approximate methods for the CDF.

**Risk allocation.** In the Florida application no further risk allocation was necessary for the calculation of disruption likelihood. However, it should be noted that the regression model was based on element and condition state definitions compliant with the AASHTO CoRe Element Guide, which has since been superseded by the AASHTO Manual for Bridge Element Inspection, where all elements have four condition states. Also, the model is influenced by Florida state and local programming practices which might differ in other states.

The analysis described here should still provide a valid estimate for future use in bridge management systems, but the use of risk allocation is recommended in order to ensure that the likelihood estimates agree with each agency's own experience.

*Table 8. Example decay index computation*

| Element data (only primary structural elements participate) | | | | Forecast condition | |
|---|---|---|---|---|---|
| **Element** | **Component** | **Quantity** | **Replacement unit cost** | **Percent in state 3** | **Percent in state 4** |
| 12/3 - Re Concrete Deck (sf.) | Deck | 16,972 | 83.85 | 10.00% | 30.00% |
| 109/3 - Pre Opn Conc Girder/Beam (lf.) | Super | 2,913 | 847.64 | 14.00% | 22.00% |
| 215/3 - Re Conc Abutment (lf.) | Sub | 213 | 1591.28 | 4.00% | 0.00% |
| 226/3 - Pre Conc Pile (ea.) | Sub | 24 | 38809.88 | 0.00% | 0.00% |
| 234/3 - Re Conc Pier Cap (lf.) | Sub | 213 | 1185.55 | 0.00% | 10.00% |
| 301/3 - Pourable Joint Seal (lf.) | Other | 210 | 71.57 | 30.00% | 30.00% |
| 310/3 - Elastomeric Bearing (ea.) | Other | 96 | 9009.48 | 0.00% | 0.00% |
| 321/3 - Re Conc Approach Slab (ea.) | Other | 1,001 | 233.15 | 10.00% | 0.00% |
| 333/3 - Other Bridge Railing (lf.) | Other | 364 | 253.92 | 0.00% | 0.00% |

| | | Current element value | | | Condition state weight | | |
|---|---|---|---|---|---|---|---|
| **Component** | **Total value (TEV)** | **State 3** | **State 4** | **Component weight** | **Weight state 3** | **Weight state 4** | **Decay index** |
| Deck | 1,423,102 | 142,310 | 426,931 | 20% | 50% | 100% | 7.00 |
| Super | 2,469,175 | 345,685 | 543,219 | 40% | 50% | 100% | 11.60 |
| Sub | 1,522,902 | 13,558 | 25,252 | 40% | 50% | 100% | 0.84 |

Decay index: **19.44**

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**Sheet LD - Fatigue**

| | | |
|---|---|---|
| 1 | Bridge ID | **010001** |
| 2 | Forecast year | **2018** |
| 3 | Hazard scenario | **Fatigue** |
| | **Screening for old steel bridges** | |
| 4 | Main material (NBI 43) | 3 - Steel |
| 5 | Main design (NBI 43) | 2 - Stringer/girder |
| 6 | Approach material (NBI 44) | 3 - Steel |
| 7 | Approach design (NBI 44) | 2 - Stringer/girder |
| 8 | Year built (NBI 27) | 1943 |
| 9 | Fracture crit (NBI 92) | N |
| | **Growth rate and initial truck volume** | |
| 10 | Funct class (26) | 14 - Urban other principal arterial |
| 11 | Average daily traffic (NBI 29) | 23,000 |
| 12 | Year of average daily traffic (NBI 30) | 2010 |
| 13 | Future average daily traffic (NBI 114) | 29,000 |
| 14 | Year of future average daily traffic (NBI 115) | 2030 |
| 15 | Growth rate (g) | 1.17% |
| 16 | Truck percent (NBI 109) | 5.50% |
| 17 | Traffic direction (NBI 102) | 2 |
| 18 | Lanes (NBI 28) | 4 |
| 19 | Single lane factor (SLF) | 0.425 |
| | If trafficdir=3 or lanes=1 | 1 |
| | If trafficdir=1 and lanes=2 | 0.85 |
| | If trafficdir=1 and lanes>2 | 0.8 |
| | If trafficdir=2 and lanes=2 or 3 | 0.5 |
| | If trafficdir=2 and lanes=4 or 5 | 0.425 |
| | If trafficdir=2 and lanes>5 | 0.4 |
| 20 | Maximum span length (NBI 48) (feet) | 100 |
| 21 | Loading cycles per truck passage ( C ) | 1 |
| 22 | First-year loading cycles ($T_1$) | 90,267 |
| | **Fatigue life** | |
| 23 | Critical detail fatigue category | E |
| 24 | Effective stress range (S) at critical detail (ksi) | 5.00 |
| 25 | Resistance factor - mean life (Table 9) | 1.6 |
| 26 | Resistance factor - evaluation life (Table 9) | 1.3 |
| 27 | Empirical fatigue constant (cu.ksi) (Table 9) | 1.10E+09 |
| 28 | No-growth mean fatigue life (years) | 156 |
| 29 | Mean fatigue life | 89 |
| 30 | No-growth evaluation fatigue life | 127 |
| 31 | Evaluation fatigue life | 78 |
| 32 | Probability of fatigue cracking | **9.31%** |

*Worksheet LD-Fatigue*

AASHTO's fatigue life model was first developed in NCHRP Project 12-28(03) and published in Report 299 (Moses et al., 1987). It was first codified in the 1990 AASHTO Guide Specification for Fatigue Evaluation of Existing Steel Bridges. With minor revisions, the model was carried over to AASHTO's Manual for Bridge Evaluation (MBE, AASHTO 2011, section 7.2.5). It was subsequently adapted for use in bridge management in NCHRP Report 495 (Fu et al 2003), and further adapted for risk assessment by the Florida Department of Transportation (Sobanjo and Thompson 2013).

The fatigue risk assessment process used in Florida has three steps:

1. Screen the bridge inventory for structures of interest: generally, older steel bridges.
2. Estimate the traffic growth rate and number of first-year loading cycles, based on NBI data.
3. Making conservative assumptions for the critical fatigue detail category and effective stress range, compute an initial estimate of the probability of fatigue cracking.
4. For bridges that appear most vulnerable in the initial calculation, locate design or rating information to determine more precisely the critical fatigue detail category and corresponding effective stress range. Then re-calculate the probability of fatigue cracking.

**Screening.** A bridge is initially selected for the risk assessment if any of the following are true:

- Main unit material (NBI 43A) is 3 or 4 (steel superstructure) and design type (NBI 43b) is between 2 and 17 inclusive;
- Approach unit material (NBI 44A) is 3 or 4 (steel superstructure) and design type (NBI 44b) is between 2 and 17 inclusive;
- Fracture critical inspections are required on the bridge (NBI 92AA)

The bridge is excluded from the analysis if it was built during or after the year 1980, or if key traffic and truck data are missing or zero.

**Loading cycles.** NBI data provide a basis for estimating the traffic growth rate, using the following formula:

$$g = \left(\frac{nbi114}{nbi29}\right) \wedge \left(\frac{1}{nbi115 - nbi30}\right) - 1 \qquad (15)$$

The first-year traffic volume can then be projected back in time using this growth rate and NBI item 29. For counting fatigue cycles, traffic volume is multiplied by the truck percent, and also multiplied by a factor to represent the normal concentration of truck traffic in the right lane.

$$T_1 = 365 \times \frac{nbi29 \times nbi109}{g\hat{}(nbi30 - nbi27)} \times SLF \times C \qquad (16)$$

Here SLF is the single-lane factor, computed as shown in the worksheet on line 19. C is the number of loading cycles per truck passage, assumed to be 1 if the maximum span length is at least 40 feet, or 2 otherwise.

**Fatigue life.** The probability of fatigue cracking is derived from the lognormal fatigue life equation. First, the mean fatigue life is computed under a scenario of no traffic growth:

$$A_M(0) = \frac{RM \times K}{T_1 S^3} \qquad (17)$$

RM is the resistance factor (unitless) for the critical fatigue category. It is given in Table 9. K is an empirical fatigue constant that was developed in the NCHRP 299 research, also given in Table 9.

In the first pass through the analysis (in Step 3), conservative assumptions are used for the critical fatigue detail category and stress range (S). For example, most bridges might be initialized with category D and a stress range of 5.0 ksi. In the second pass, this information can be tightened up by reference to design or load rating information for bridges found to be potentially vulnerable.

*Table 9. Fatigue life parameters*

| Fatigue constants | | | |
|---|---|---|---|
| Fatigue category | RM | RE | K ($ksi^3$) |
| A | 2.8 | 1.7 | 2.50 E+10 |
| B | 2.0 | 1.4 | 1.20 E+10 |
| B’ | 2.4 | 1.5 | 6.10 E+09 |
| C | 1.3 | 1.2 | 4.39 E+09 |
| C’ | 1.3 | 1.2 | 4.39 E+09 |
| D | 1.6 | 1.3 | 2.20 E+09 |
| E | 1.6 | 1.3 | 1.10 E+09 |
| E’ | 2.5 | 1.6 | 3.90 E+08 |

If the growth rate g is greater than or less than zero, the formula is modified as follows:

$$A_M(g) = \frac{\log(A_M(0) \times g + 1)}{\log(g + 1)} \qquad (18)$$

If the expression inside the upper log expression $(A_M(0) \times g + 1)$ is less than or equal to zero, then the fatigue probability is assumed to be zero.

A second point on the fatigue life distribution, one standard deviation earlier, is computed by substituting RE in place of RM from Table 9 into equations 17 and 18, to yield the evaluation fatigue life $A_E$. Then the fatigue probability is computed from the formula:

$$P = LOGNORMDIST\left(\frac{A}{A_M}, 0, ln\left(\frac{A_M}{A_E}\right)\right) \qquad (19)$$

In this equation LOGNORMDIST is the Excel function for the cumulative lognormal distribution with a mean of zero and a standard deviation of $\ln(AM/AE)$. For other computational platforms, library functions or standard statistical texts should be consulted for appropriate methods to compute or approximate this function.

**Risk allocation.** This model computes the likelihood of fatigue cracking, which is a broader scenario than service disruption since most fatigue cracks do not cause a disruption of transportation service. It is necessary to follow this analysis with a risk allocation step in order to scale the probability so it agrees with agency experience with bridges that are disrupted due to fatigue.

## 3.5 Estimate consequences of service disruption

NCHRP 20-07 (378) Risk Analysis

**Sheet CQ - Cost**

| | | | | |
|---|---|---|---|---|
| 1 | Bridge ID | **010001** | | |
| 2 | Forecast year | **2018** | | |
| 3 | Hazard scenario | **Fatigue** | | |
| | **Cost of Incident Response (historical analysis and polling)** | | | |
| 4 | Estimated costs associated with traffic control | | | |
| 5 | Estimated costs associated with incident response | | | |
| 6 | Estimated costs associated with HazMat remediation | | | |
| 7 | Estimated total expenditures of incident response | 0 | | |
| | **Cost of Recovery (historical analysis and polling)** | | | |
| 9 | Estimated costs associated with detour | | | |
| 10 | Estimated costs associated with debris removal | | | |
| 11 | Estimated cost of temporary bridge (if used) | | | |
| 12 | Estimated total expenditures of recovery | 0 | | |
| | **Cost of Repair/Replacement** | | | |
| 13 | Bridge Type (Select from drop-down list) | Medium Span | | |
| 14 | Enter sq. ft. of bridge to be repaired/replaced | 100000 | | |
| 15 | Enter range of estimated cost per sq. ft. | | | |
| 16 | Low estimated cost per sq. ft. | 135 | | |
| 17 | High estimated cost per sq. ft. | 170 | | |
| 18 | Estimated cost of replacement bridge ($M) | 13.5 | - | 17 |
| 19 | Estimated cost of bridge repair | | | |
| 20 | Enter percentage of replacement cost 68% | 9.18 | - | 11.56 |

### *Worksheet CQ-Cost*

Bridge infrastructures are critical components of roadway networks. The failure of a bridge can result in significant economic consequences. A bridge infrastructure failure can be decomposed into infrastructure cost, human cost, environmental cost, traffic delay cost, as well as economic cost consequences.

The computation of infrastructure costs as a consequence of service disruption includes the costs of responding to the disruption (e.g. incident response, traffic control, HazMat remediation) and the costs of recovery (e.g. costs of detour, debris removal, and any temporary structures put in place) along with the cost of repairing or replacing the damaged or failed bridge.

Estimating the cost of a bridge replacement can be a complex process, as costs can vary depending upon location, type of bridge, length of bridge, etc.  A universally accepted practice is to compute a cost per square foot. For example, the Florida Department of Transportation (FDOT 2014) has compiled a reference list of square foot costs for various bridge types using historical data from recent bridge replacement projects (see Section 5.3). The FHWA computes and publishes bridge replacement unit values per state annually as part of the National Bridge Inventory based on bridge data submitted by the States, Federal agencies, and Tribal governments.

A consequence analysis takes an economic approach to estimate the human, environmental, traffic delay as well as the economic cost consequences of a bridge being taken out of service. The analysis includes factors that will directly impact a state's economy such as increased time spent in vehicles and job losses as employers react to a possible temporary decline in sales. For example, after the Minnesota I-35W bridge collapse, a Mn/DOT study (Minnesota DOT 2008) focused on valuing how the unavailability of the river crossing affected road-users and assigned monetary values to auto travel time, heavy commercial truck travel time, as well as to variable operating costs for both – an approach further discussed in Worksheet CQ-Mobility later in this section.

NCHRP 20-07 (378) Risk Analysis

**Sheet CQ - Safety**

| | | |
|---|---|---|
| 1 | Bridge ID | **010001** |
| 2 | Forecast year | **2018** |
| 3 | Hazard scenario | **Earthquake** |
| | **Prediction of traffic volume** | |
| 4 | Average daily traffic (NBI 29) | 23,000 |
| 5 | Year of average daily traffic (NBI 30) | 2010 |
| 6 | Future average daily traffic (NBI 114) | 29,000 |
| 7 | Year of future average daily traffic (NBI 115) | 2030 |
| 8 | Growth rate (g) | 1.17% |
| 9 | Projected average daily traffic (ADT) | 25,235 |
| 10 | Social cost per vehicle in crash (ACC$) ($) | 43,694 |
| | **Sudden collapse scenario** | |
| 11 | Funct class (26) | 14 - Urban other principal arterial |
| 12 | Speed on affected roadway (RS) (mph) | 40 |
| 13 | Length of affected roadway (L) (feet) | 230 |
| 14 | Number of vehicles in crash (VC) | 1.1450 |
| 15 | Total social cost | **50,031** |
| 16 | Speed for worst consequences | 5 |
| 17 | Consequence ratio (CR) | **12.50%** |

NCHRP 20-07 (378) Risk Analysis

**Sheet CQ - Safety**

| | |
|---|---|
| Bridge ID | **010001** |
| Hazard scenario | **Earthquake** |

Mitigation effectiveness - Percent of vehicles damaged

| Range | Damage | Use value | Check one |
|---|---|---|---|
| Ineffective | >= 95 | 100 | ○ |
| Low | < 95 | 75 | ○ |
| Moderate | < 65 | 50 | ○ |
| High | < 35 | 25 | ○ |
| Reliable | < 5 | 0 | ○ |
| | | Specific percentage (optional) | |

### *Worksheet CQ-Safety*

Safety consequences of a hazard scenario depend significantly on the suddenness of the incident. Typical operational practices of transportation agencies and law enforcement would tend to restrict access when safety is threatened, if sufficient warning is available. This would reduce the safety consequence but might increase the cost and mobility consequences. Hazards where advance warning cannot be expected include:

Earthquake
Landslide
Vessel collision
Sabotage

Overload
Over-height truck impact
Truck collision

In these sudden incidents, potentially all of the vehicles on and under the structure at the time of the event are at risk. However, unless the structure collapses, the loss rate would typically be much less.

In most cases where safety impacts exist, the consequence is proportional to the number of vehicles involved in a crash, which, in turn, is proportional to traffic volume. Certain hazard scenarios, such as overload, over-height truck impact and truck collision, always involve at least one vehicle and may involve additional vehicles with a probability in proportion to traffic volume.

Certain hazards are less likely to have safety consequences because of the potential for advance warning:

Storm surge
High wind
Flood
Scour
Wildfire
Extreme temperature
Permafrost instability
Advanced deterioration
Fatigue

The agency would typically discount the maximum possible consequences for these hazard scenarios because of the likelihood that much of the normal daily traffic stream would be able to avoid losses.

**Consequence cost**. The AASHTO Red Book (AASHTO 2010) has procedures and research-based metrics which take into account typical crash injury severity rates and property damage. For bridge risk analysis, it is appropriate to use the figures on page 5-24, using the average over all vehicle classes and accident types. This excludes insurance reimbursement to avoid double-counting of costs. The calculation is 3.394 vehicle accidents per million VMT, divided by \$0.1062 per VMT. Updated to 2016 dollars using the Consumer Price Index (BLS 2016), this figure is \$43,694 per vehicle per crash. The safety consequence is then:

$$CQ_b = 43{,}694 \times VC_h \qquad (20)$$

$VC_h$ = count of vehicles involved in the crash

The vehicle loss rate is most easily established using the polling method. District maintenance personnel are asked to list recent hazard events, and indicate the number of vehicles damaged as a result of those events. The AASHTO Red Book metrics account for injuries and fatalities in addition to the vehicle damage.

For a worst-case scenario where a structure collapses while in service, the vehicle count can be estimated from:

$$VC_h = \frac{ADT_b}{24} \times \frac{1}{RS} \times \frac{length}{5280} \qquad (21)$$

Where $length$ is the bridge length for roadways on the bridge, and bridge width for roadways under a bridge. If the likelihood of a crash depends on traffic volume (over-height truck collisions, for example), the speed and traffic volume should reflect a busy time of day. If the likelihood does not depend on traffic volume (e.g. earthquakes), then a daily average of speed and volume should be used.

Since speed is not an NBI data item, agencies may want to obtain it from their geographic information systems, HPMS data, or as part of the inspection process. Another option is to use the default speeds by functional class that have long been used in the AASHTO Pontis Bridge Management System (Cambridge 2003), reproduced in Table 10.

*Table 10. Suggested default speeds by functional class (Cambridge 2003)*

| Default bridge speeds from Pontis | |
|---|---|
| Functional class | Default speed (mph) |
| 1 Rural interstate | 60 |
| 2 Rural Principal Arterial | 55 |
| 6 Rural Minor Arterial | 50 |
| 7 Rural Major Collector | 50 |
| 8 Rural Minor Collector | 25 |
| 9 Rural Local | 25 |
| 11 Urban Interstate | 55 |
| 12 Urban Freeways | 50 |
| 14 Urban Principal Arterial | 50 |
| 16 Urban Minor Arterial | 30 |
| 17 Urban Collector | 30 |
| 19 Urban Local | 20 |

The worksheet shows how to use NBI data to estimate traffic volume, and then proceeds through an example of equation 21. Traffic growth rate is computed from:

$$g = \left(\frac{nbi114}{nbi29}\right) ^\wedge \left(\frac{1}{nbi115 - nbi30}\right) - 1 \qquad (22)$$

$$ADT = nbi29 \times (1 + g)^\wedge(FY - nbi30) \qquad (23)$$

Where FY is the year for which consequences are to be forecast.

**Mitigation effectiveness.** For many hazards, mitigation effectiveness determines whether an extreme event causes collapse, or merely causes a brief closure for inspection. For example, seismic restraining devices are meant to accomplish this. Similarly, seismic column wraps and other design features such as plastic hinges may allow a structure to remain standing for evacuation purposes even though it will still need to be replaced. Mobility and cost consequences will occur, but safety consequences are avoided.

Mitigation effectiveness can be assessed as part of the likelihood of service disruption, for example in Worksheet LD-Flood. If the hazard scenario includes service disrupted because of temporary closures for inspection, then this is appropriate. If the hazard scenario does not include these temporary closures, but only more consequential incidents, then it is appropriate to add a mitigation effectiveness factor to equation 21, and use a field assessment to determine the value of this factor:

$$VC_h = ME_b \times \frac{ADT_b}{24} \times \frac{1}{RS} \times \frac{length}{5280} \qquad (24)$$

Here $ME_b$ is the result of the field assessment, depicted in the lower worksheet at the beginning of this section. A value of 100% indicates that no mitigation is present, or it is judged to be ineffective. A value of 0% indicates mitigation that is reliably effective. The agency will want to establish criteria for this assessment that correspond to the types of mitigation measures it uses and the expected structural response.

In AASHTOWare Bridge Management, the Assessment feature provides two dimensions, one for likelihood and one for consequence. See Figure 4 earlier in these Guidelines. The likelihood portion can be used for the broader likelihood of service disruption, allowing for even temporary disruptions. The consequence portion can be used for a purpose such as the mitigation effectiveness term, to influence the forecast severity of safety-related outcomes.

NCHRP 20-07 (378) Risk Analysis

**Sheet CQ - Mobility**

| | | |
|---|---|---|
| 1 | Bridge ID | **010001** |
| 2 | Forecast year | **2018** |
| 3 | Hazard scenario | **Earthquake** |
| | **Prediction of traffic volume** | |
| 4 | Average daily traffic (NBI 29) | 23,000 |
| 5 | Year of average daily traffic (NBI 30) | 2010 |
| 6 | Future average daily traffic (NBI 114) | 29,000 |
| 7 | Year of future average daily traffic (NBI 115) | 2030 |
| 8 | Growth rate (g) | 1.17% |
| 9 | Projected average daily traffic (ADT) | 25,235 |
| | **Cost of detoured traffic** | |
| 10 | Funct class (26) | 14 - Urban other principal arterial |
| 11 | Duration of the disruption (DD) (hours) | 5.0 |
| 12 | Detour length (DL, NBI 19) (miles) | 2.2 |
| 13 | Vehicle operating cost (VOC$) ($/mile) | 0.208 |
| 14 | Detour speed (DS) (mph) | 45 |
| 15 | Travel time cost (TT$) ($/hour) | 30.62 |
| 16 | Vehicle occupancy (VO) (persons/vehicle) | 1.30 |
| 17 | Total Social Cost | **12,637** |
| 18 | Worst case duration (hours) | 720 |
| 19 | Consequence ratio (CR) | **0.69%** |

*Table 11. Default detour speeds (Cambridge 2003)*

| Default detour speeds from Pontis | |
|---|---|
| Functional class | Detour speed (mph) |
| 1 Rural interstate | 50 |
| 2 Rural Principal Arterial | 45 |
| 6 Rural Minor Arterial | 40 |
| 7 Rural Major Collector | 40 |
| 8 Rural Minor Collector | 20 |
| 9 Rural Local | 20 |
| 11 Urban Interstate | 45 |
| 12 Urban Freeways | 40 |
| 14 Urban Principal Arterial | 40 |
| 16 Urban Minor Arterial | 25 |
| 17 Urban Collector | 25 |
| 19 Urban Local | 15 |

### *Worksheet CQ-Mobility*

Mobility consequences usually entail detours while a bridge is monitored, repaired, or rebuilt, but may have smaller impacts such as truck restrictions or speed reductions.

**Consequence cost**. The recommended model for mobility consequences is actually the same model as used in AASHTOWare Bridge Management for mobility impacts of functional deficiencies. The mobility cost per event is:

$$CQ_b = ADT_b \times \frac{DD_b DL_b}{24} \times \left( VOC\$ + \frac{TT\$ \times VO}{DS_b} \right) \quad (25)$$

$ADT$ = forecast vehicles per day affected
$DD$ = the duration of the disruption, in hours
$DL$ =the detour length in miles
$VOC\$$ = the average vehicle operating cost per mile
$DS$ = the detour speed in mph
$TT\$$ = travel time cost per hour
$VO$ = the average vehicle occupancy rate

Traffic volume is forecast in the same manner as for safety, in the previous section. Detour speed may be available in the Department's geographic information system. In the absence of this, AASHTO's Pontis system provided a default detour speed equal to 80% of the default bridge speed, assigned by functional class. Table 11 provides these default speeds.

Detour duration is typically an assessment based on accessibility of the bridge site and the extent of damage anticipated from each hazard scenario.

Vehicle operating cost can be developed from the AASHTO Red Book, page 5-10. This is based on the "large car" column and includes fuel, oil, maintenance, and tires. Updated to 2016 dollars using the Consumer Price Index (BLS 2016), this cost is $0.208 per mile.

Travel time cost can be developed from the AASHTO Red Book, page 5-4. This figure uses the average over all occupations, computed as an opportunity cost. Updated to 2016 dollars using the Consumer Price Index, this cost is $30.62 per hour.

Average vehicle occupancy is an estimate also suggested by the AASHTO Red Book, but individual agencies may have developed their own estimates for transportation planning purposes.

NCHRP 20-07 (378) Risk Analysis

**Sheet CQ - Environmental sustainability**

| | | |
|---|---|---|
| 1 | Bridge ID | **010001** |
| 2 | Forecast year | **2018** |
| 3 | Hazard scenario | **Earthquake** |
| | **Prediction of traffic volume** | |
| 4 | Average daily traffic (NBI 29) | 23,000 |
| 5 | Year of average daily traffic (NBI 30) | 2010 |
| 6 | Future average daily traffic (NBI 114) | 29,000 |
| 7 | Year of future average daily traffic (NBI 115) | 2030 |
| 8 | Growth rate (g) | 1.17% |
| 9 | Projected average daily traffic (ADT) | 25,235 |
| | **Computation of emissions damage costs** | |
| 10 | Funct class (26) | 14 - Urban other principal arterial |
| 11 | Detour speed (DS) (mph) | 40 |
| 12 | Duration of the disruption (DD) (hours) | 720.0 |
| 13 | Detour length (DL, NBI 19) (miles) | 2.2 |
| 14 | Vehicle emissions cost (EC$) ($/mile) | 0.0196 |
| 15 | Total Social Cost | **32,643** |
| 16 | Worst case duration (hours) | 720 |
| 17 | Consequence ratio (CR) | **100.00%** |

### *Worksheet CQ-Environment*

For environmental sustainability, the approach recommended in NCHRP Report 590 (Patidar et al 2007) assigns a judgment-based utility value using a group elicitation process. This is a reasonable approach, but it is important to validate it by application in a BMS to determine if projects having environmental consequences are prioritized appropriately. Adjustments in the parameter may be necessary to secure the desired behaviour of the model.

Another more objective approach is used in FHWA's Highway Economic Requirements System (HERS) (FHWA 2005, Appendix F). This methodology, updated from earlier research in California (Booz et al 1999), relies on a study that simulates vehicular air pollution emissions under various scenarios of congestion, speed, and volume. Six pollutants are included in the analysis: carbon monoxide, volatile organic compounds, oxides of nitrogen, sulfur oxides, small particulate matter, and road dust. The study uses earlier research on the economic impact on health and property damage caused by these pollutants.

**Consequence cost**. The relevant portion of the model concerns changes in speed or travel distance as a result of service disruptions. The researchers produced a set of tables that provide a straight-forward estimate of emission damage cost per vehicle-mile as a function of functional class and speed. The application would be very similar to the mobility relationship described above.

$$CQ_b = ADT_b \times \frac{DD_b DL_b}{24} \times EC\$ \qquad (26)$$

$ADT$ = forecast vehicles per day affected
$DD$ = the duration of the disruption, in hours
$DL$ =the detour length in miles
$EC\$$ = emission damage cost ($/vehicle-mile)

The duration of the disruption is the same as the assessment used for mobility consequences. It will depend on the definition of the hazard scenario and ideally would be assessed by a person with knowledge of the site, using a set of agency-defined criteria. Typically it is the length of time that traffic must be detoured if the service disruption takes place.

Emission damage cost is summarized in Table 12, based on the data provided in FHWA (2005). The FHWA report provides the cost estimates disaggregated by vehicle class – four-tire vehicles, single-unit trucks, and combination trucks. Therefore 2013 FHWA statistics on vehicle-miles travelled (FHWA 2015) were used to develop weighted averages. These were updated to 2016 dollars using the consumer price index (BLS 2016). If detour speed is not available, the Pontis default values can be used, as presented in the previous section. Table 13 then shows the resulting emissions costs.

It is important to note that this methodology does not consider carbon dioxide emissions, nor does it include potential losses to water, agricultural, recreational, or cultural resources. These would be attractive areas for future research.

*Table 12. Emissions damage costs (adapted from FHWA 2005)*

| Emission damage cost in 2016 $ per vehicle-mile | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Detour speed (mph) | | | | | | | | | | | | | |
| | Functional class | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 |
| 1 | Rural interstate | 0.0805 | 0.0627 | 0.0548 | 0.0510 | 0.0478 | 0.0478 | 0.0472 | 0.0475 | 0.0484 | 0.0500 | 0.0525 | 0.0562 | 0.0616 | 0.0669 |
| 2 | Rural Principal Arterial | 0.0620 | 0.0437 | 0.0370 | 0.0330 | 0.0309 | 0.0297 | 0.0290 | 0.0295 | 0.0296 | 0.0303 | 0.0315 | 0.0333 | 0.0358 | 0.0382 |
| 6 | Rural Minor Arterial | 0.0619 | 0.0436 | 0.0369 | 0.0329 | 0.0308 | 0.0296 | 0.0289 | 0.0294 | 0.0295 | 0.0302 | 0.0314 | 0.0332 | 0.0356 | 0.0381 |
| 7 | Rural Major Collector | 0.0565 | 0.0386 | 0.0323 | 0.0288 | 0.0270 | 0.0258 | 0.0252 | 0.0254 | 0.0255 | 0.0259 | 0.0266 | 0.0275 | 0.0288 | 0.0301 |
| 8 | Rural Minor Collector | 0.0565 | 0.0386 | 0.0323 | 0.0288 | 0.0270 | 0.0258 | 0.0252 | 0.0254 | 0.0255 | 0.0259 | 0.0266 | 0.0275 | 0.0288 | 0.0301 |
| 9 | Rural Local | 0.0565 | 0.0386 | 0.0323 | 0.0288 | 0.0270 | 0.0258 | 0.0252 | 0.0254 | 0.0255 | 0.0259 | 0.0266 | 0.0275 | 0.0288 | 0.0301 |
| 11 | Urban Interstate | 0.0500 | 0.0363 | 0.0312 | 0.0294 | 0.0284 | 0.0277 | 0.0274 | 0.0275 | 0.0279 | 0.0286 | 0.0296 | 0.0311 | 0.0333 | 0.0355 |
| 12 | Urban Freeways | 0.0407 | 0.0276 | 0.0232 | 0.0220 | 0.0213 | 0.0208 | 0.0205 | 0.0205 | 0.0207 | 0.0210 | 0.0215 | 0.0221 | 0.0229 | 0.0238 |
| 14 | Urban Principal Arterial | 0.0416 | 0.0286 | 0.0246 | 0.0222 | 0.0208 | 0.0200 | 0.0195 | 0.0196 | 0.0198 | 0.0201 | 0.0206 | 0.0212 | 0.0221 | 0.0231 |
| 16 | Urban Minor Arterial | 0.0413 | 0.0284 | 0.0245 | 0.0221 | 0.0207 | 0.0198 | 0.0194 | 0.0194 | 0.0196 | 0.0199 | 0.0204 | 0.0210 | 0.0219 | 0.0228 |
| 17 | Urban Collector | 0.0413 | 0.0284 | 0.0244 | 0.0220 | 0.0206 | 0.0198 | 0.0193 | 0.0194 | 0.0196 | 0.0199 | 0.0203 | 0.0210 | 0.0218 | 0.0227 |
| 19 | Urban Local | 0.0413 | 0.0284 | 0.0244 | 0.0220 | 0.0206 | 0.0198 | 0.0193 | 0.0194 | 0.0196 | 0.0199 | 0.0203 | 0.0210 | 0.0218 | 0.0227 |

*Table 13. Emissions damage costs using default detour speeds*

| Emission cost using default detour speed | | | |
|---|---|---|---|
| | Functional class | Detour speed (mph) | Emission cost ($/VMT) |
| 1 | Rural interstate | 50 | 0.0500 |
| 2 | Rural Principal Arterial | 45 | 0.0296 |
| 6 | Rural Minor Arterial | 40 | 0.0294 |
| 7 | Rural Major Collector | 40 | 0.0254 |
| 8 | Rural Minor Collector | 20 | 0.0288 |
| 9 | Rural Local | 20 | 0.0288 |
| 11 | Urban Interstate | 45 | 0.0279 |
| 12 | Urban Freeways | 40 | 0.0205 |
| 14 | Urban Principal Arterial | 40 | 0.0196 |
| 16 | Urban Minor Arterial | 25 | 0.0207 |
| 17 | Urban Collector | 25 | 0.0206 |
| 19 | Urban Local | 15 | 0.0244 |

# 4. Applications to risk management

Risk management consists of a spectrum of activities that a transportation agency can take to resolve identified risks, viewed in context of transportation business and environmental control factors.

These activities include:

- Risk avoidance – eliminating sources of the risk. This is typically not an option for transportation agency as it is difficult, if not impossible, to refrain from engaging in risky activity.
- Risk reduction – implementing actions that lower risk to the agency. Risk reduction techniques, such as identifying and eliminating vulnerabilities, is one method of reducing or mitigating losses.
- Risk spreading – distribution of risk across various program areas or activities. Risk spreading recognizes that all parties or providers to the transportation systems network including vendors, suppliers, contractors, and the tribal/local/state/national government share responsibility to deploy mitigation strategies and countermeasures that will reduce the vulnerabilities and increase the resiliency of the system.
- Risk transfer – use of insurance to cover costs that would be incurred as result of loss. The use of insurance to transfer all or parts of liability to another business or entity is one of the traditional market mechanisms for estimating, pricing, and distributing risk.
- Risk acceptance – knowledgeable determination that a risk is best managed by taking no action at all. Typically cost benefit analysis can be utilized to determine the tipping point where expending funds to fix a problem exceeds the return on investment that the mitigation achieves. Regional and local variation in tolerance to risk, social or funding priorities, and the owners' institutional experience combine to provide different levels of risk acceptance.

Although Risk Transfer and Risk Acceptance may be acceptable risk response strategies in some situations, the transportation industry often faces potential for loss of life and in such cases these strategies are rarely an option.

Risk management in terms of bridge management can be defined as evaluating alternative countermeasures, or mitigation treatments, and design requirements and selecting amongst them based on their effectiveness in mitigating threats and on their costs.

## 4.1 Risk mitigation treatments

According to the DHS Risk Lexicon (DHS 2010), mitigation is the application of a measure or measures to reduce the likelihood of an unwanted occurrence and/or its consequences. There are many measures and approaches available to transportation agencies to address the hazards and site-based risks of bridge assets. The countermeasures encompass at least four distinct categories:

- Physical security countermeasures that include lighting, barriers, fences, CCTV, intrusion detection devices, and physical inspections.
- Access control countermeasures such as restricted parking, random inspections, limited access points, automatic warning systems, and visible signage.
- Design/Engineering countermeasures including seismic retrofitting, encasement/jacketing¸ scour protection, preservation approaches, fender and other protection systems.
- Operational Countermeasures such as patrols, warning systems, monitoring and data collection, training, and planned redundancy (detours).

Table14 on the following pages provide a list of potential countermeasures by hazard along with references to relevant guidance information.

*Table 14: Countermeasures by Hazard*

| Hazard | Countermeasures | Guidance References |
|---|---|---|
| Earthquakes | Seismic retrofitting such as restrainers, seat extensions, column jackets, footing overlays, soil remediation, and energy-dissipating bearings. | LRFD Seismic Analysis and Design of Bridges Reference Manual, 2014<br><br>FHWA Seismic Retrofitting for Highway Structures, 2006 |
| Landslide | • Scaling, slope screening, catch fences, excavation, artificial reinforcement, shotcrete, barrier systems, rock buttress construction; and soil nailing (inserting reinforcement bars to stabilize steep slopes).<br>• Drainage systems such as installation of subsurface drainage facilities<br>• Retaining walls and viaducts to protect from further landslides. | Rockfall Hazard Rating System, FHWA, 1992 |
| Storm Surge | • Add /enhance shoreline revetments. Increased footprint of shoreline revetment may cause increased environmental impacts.<br>• Elevate approach roadways.<br>• Extend wing walls, add/enhance scour protection, strengthen deck tie-downs | NCHRP Report 750 – Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report, 2014 |
| High Winds | • Upsize/strengthen beams/girders as required<br>• Upsize or add wind / lateral bracing elements (dampening devices on cable bridges)<br>• Add/ strengthen deck tie-downs<br>• Enhance scour countermeasures | AASHTO standards and ASCE 7-05 guidelines for design standards for wind loading and bridges. |
| Floods | • Install Floodplain culverts<br>• Harden slopes of approach roadway<br>• Elevate approach roadways<br>• Extend wing walls, add/enhance scour protection, strengthen deck tie-downs<br>• Add/raise spans<br>• Add protective coatings | NCHRP Report 750 – Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report, 2014<br><br>HEC-18 FHWA, 2012 |
| Scour | • Upstream or downstream channel control, armoring, flow modification, bridge modification, and drainage control.<br>o Upstream channel control incudes spur dikes, hard points, or vanes that prevent channel from migrating laterally and bypassing the bridge opening.<br>o Downstream control includes a weir or checkdam to prevent headcuts from migrating upstream and threatening bridge.<br>o Armoring consists of riprap or cable-tied blocks that protect the soil from scour.<br>• Bridge modification means adding an additional span to allow increased flow area, and flow modification entails guiding the flow smoothly through the bridge opening, typically with a wall of some kind. Drainage control ensures no adverse impact from drainage water around the bridge. | NCHRP Report 587 Countermeasures to Protect Bridge Abutments from Scour, 2007<br><br>Optimal Bridge Retrofit Strategy to Enhance Disaster Resilience of Highway Transportation Systems, US DOT RITA 2014 |
| Wildfire | • Post-wildfire debris flow mitigation includes watershed-wide erosion control, interception of the debris above by deflection of flow away from bridge, debris basins, or high tensile steel netting or pipes, or passing the debris through a culvert or under a bridge.<br>• Passive fire protection such as fire resistive coatings, | Evaluation Of Debris Flow Removal Protocol, Mitigation Methods, And Development Of A Field Data Sheet, CDOT, 2006 |

| | | |
|---|---|---|
| | intumescent coatings, and fire resistant materials | |
| Extreme Temperature | • Widen expansion joints<br>• Redesign bearings<br>• Strengthen beams and girders | NCHRP Report 750 – Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report, 2014 |
| Permafrost Instability | • Mitigation techniques such as use of reflective surfaces, air convection embankment, geosynthetic reinforcement, thermosyphons, berms, air ducts, insulation materials and lightweight fill materials. | NCHRP Report 750 – Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report, 2014 |
| Overloads | • Real-time monitoring and diagnosis<br>• Timely damage detection, safety evaluation and necessary precautions<br>• Strengthening<br>• Increased enforcement | FHWA Manual on Uniform Traffic Control Devices (MUTCD)<br><br>Bridge Analysis and Evaluation of Effects under Overload Vehicles, CFIRE 2009 |
| Over-height Collisions | • Overheight warning systems<br>• "Bridge Bumper" to maximize energy absorption and decrease likelihood of damage/fatalities<br>• Bridge raising | FHWA Manual on Uniform Traffic Control Devices (MUTCD)<br><br>Sharma, H. and Hurlebaus, S. (2012) Overheight Collision Protection Measures for Bridges. Structures Congress 2012: pp. 790-797. |
| Vehicle Collisions | • Improve operational safety features<br>• Accident reduction through rational design choices<br>• Improving highway safety features can therefore lead to a reduction in fire risk, providing a dual benefit.<br>• Bridge Protective Beam Wrap to prevent debris from falling on the roadway/traffic in the event that the beam is impacted<br>• Single slope concrete barrier (or 42-in tall, Test Level 5 approved barrier equivalent) to mitigate lateral impacts | AASHTO LRFD Bridge Design Specifications 2012 Section 3.6.5-Vehicular Collision Force<br><br>AASHTO Highway Safety Design Manual (HSM).<br><br>Texas Transportation Institute (TTI) "Guidelines for Designing Bridge Piers and Abutments for Vehicle Collisions." ---Technical Reports 9-4973-1 and 9-4973-2<br><br>BRIDGE PROTECTIVE BEAM WRAP" Standard (BPBW)<br>Issued as a Bridge Standard on July 10, 2013<br><br>Highway Bridge Fire Hazard Assessment and Guide Specification for Fire Damage Evaluation in Steel Bridges, NCHRP 12-85, 2013 |
| Vessel Collisions | • Fender systems including timber, rubber, concrete, and steel fenders<br>• Pile-supported systems<br>• Protection systems such as dolphin protection, island protection, and floating protection systems<br>• Movable bridge protection<br>• Motorist warning systems such as hazard detection systems, verification devices, traffic control and information devices | Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges, 2nd Edition, with 2010 Interim Revisions |

| | | |
|---|---|---|
| Terrorism/Countering Violent Extremism | • Increase standoff distance with physical deterrents such as bollards, security fences, and vehicle barriers<br>• Increasing the design category and detailing requirements for reinforced bridge columns designed for blast loads<br>• Physical security countermeasures such as lighting, barriers, fences, CCTV, intrusion detection devices, and physical inspections.<br>• Access control countermeasures such as restricted parking, random inspections, limited access points, explosive detection and visible signage. | NCHRP Report 645: Blast-Resistant Highway Bridges: Design and Detailing Guidelines, 2010<br><br>NCHRP Report 525 Surface Transportation Security Volume 14 Security 101: A Physical Security Primer for Transportation Agencies, 2009<br><br>ASTM C 825 –Standard Specification for Precast Concrete Barriers<br><br>NCHRP 350 –Recommended Procedures for the Safety Performance Evaluation of Highway Features, 2004 |
| Advanced Deterioration | • Preservation or rehabilitation activities such as partial or complete deck replacement; superstructure replacement; strengthening.<br>• Preventive maintenance such as sealing or replacement of leaking joints; Installation of deck overlays; Installation of cathodic protection (CP) systems; Complete, spot, or zone painting/coating of steel structural elements; Installation of scour countermeasures. | Bridge Preservation Guide, FHWA 2011 |
| Fatigue | • Repair and retrofit techniques such as surface treatments, crack arrest methods, repair of through-thickness cracks, and modification of the connection or structure to reduce the cause of cracking. | Manual for Repair and Retrofit of Fatigue Cracks in Steel Bridges, FHWA 2013<br><br>NCHRP Report 721 Fatigue Evaluation of Steel Bridges, 2012 |

## 4.2 Level of service standards

Level of service classifications or standards describe the quality of service offered to road users. A hazard event can result in loss of functionality that requires road closures, traffic delays, and traffic detours. The resulting reduction in the level of service impacts both the community and the regional (and potentially national) economy.

In order to decide whether to consider a mitigation action, needs and priorities should be clarified in a manner that reflects the mission of the state DOT as well as the broader concerns of the community quality of life and economic welfare. That includes identifying the level of risk transportation managers are willing to accept and determining the collectively acceptable levels of service that communities and economic regions require. DOT agency experience and regional/ local variation in tolerance will provide different threshold service levels.

NCHRP Report 525 Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA) (SAIC 2009) utilizes three types of thresholds to determine which assets should be considered for mitigation countermeasures:

- Potentially Exposed Population – determined by number of people at risk from the hazard or threat.
- Property loss – estimated using asset replacement costs.
- Mission importance – either an estimation of transport delays using Average Daily Traffic (ADT) and Detour length or a designation based on route importance (e.g. evacuation route, major freight route, access to critical economic assets, etc.)

Level of service thresholds for mitigation actions can be developed using a variety of elements to assess what level of service can be provided after a disruption.

- Reduction in ADT –what is the impact on functionality?
- Reduction in truck traffic – what is the economic impact?
- Detour length or availability – how much traffic delay will occur?
- Route importance or mission importance –is it on a major transportation route? is it part of an evacuation route? Is it historically or culturally significant?

- Potential Regional Transportation Impact – is it part of a regional transport network?

## 4.3 Mitigation costs and effectiveness

Mitigation measures often require long-term investments and, in some cases, large capital outlays in the context of uncertainty regarding hazard risks and the availability of funding. The benefits of investments in countermeasures can be widely distributed accruing both to the transportation agencies and the populations that depend on this infrastructure for mobility and access to goods and services.

As part of the evaluation of mitigation costs, the cost of inaction, i.e. the cost of continually repairing assets impacted by hazards such as floods, landslides, and other events, should be recognized. For example, from 1995-2000 the Oregon Department of Transportation spent approximately $22.3 million on landslide repairs along U.S. Highway 101, much of which was performed under emergency conditions.

The criteria for selecting a countermeasure usually encompass the following set of considerations at a minimum:

- technical effectiveness (including no substantial adverse effects)
- constructability
- durability and maintainability
- aesthetics
- environmental issues
- cost.

See the guidance resources listed in Table 14 in section 4.1 for information about countermeasure in terms of these considerations. The CAPTool developed as part of NCHRP Report 525 Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA) (SAIC 2009) provides an Excel spreadsheet tool with estimates of countermeasure effectiveness by hazard and asset class (including bridges) categorized as High, Medium and Low effectiveness for each hazard (orange indicates high effectiveness, yellow indicates medium effectiveness and grey indicates low effectiveness). Figure 14 provides an illustration of the Effectiveness Matrix in the CAPTool.

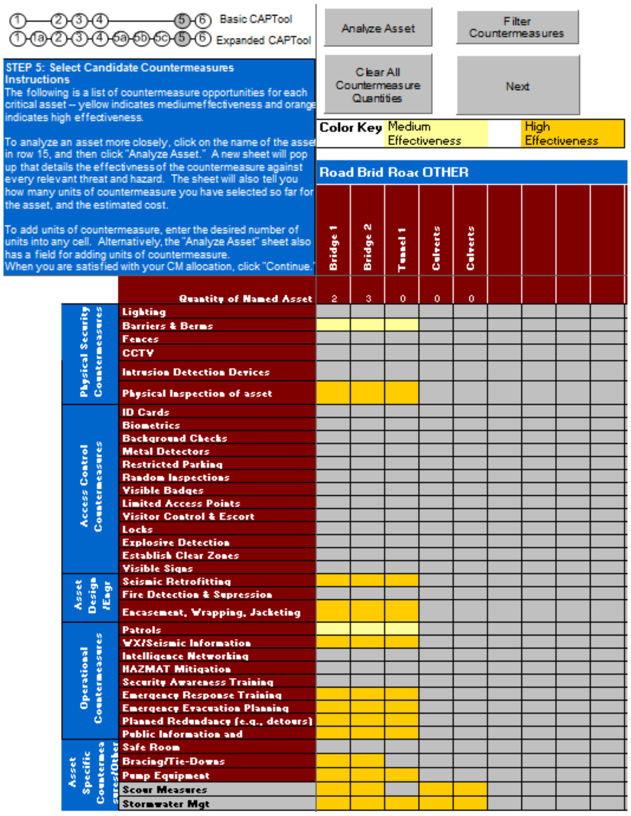


*Figure 14: Countermeasure Effectiveness in CAPTool*

Costs per countermeasure are included in the Countermeasure Dictionary within CAPTool. Mitigation cost estimates for capital budgeting purposes for the assets selected are provided in the CAPTool Results Report.

A tool was developed as part of NCHRP Report 750 Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report (Mayer 2014) that provides effective engineering options for climate stressor mitigation with relative costs identified as a potential percentage increase of project costs (ranging from a 1-5% increase for low to a greater than 25% increase for a very high).

## 4.4 Incorporating risk in asset management

All of the tools presented in these Guidelines are developed with the objective of using a bridge management system to simultaneously support both risk management and asset management; in other words, to fully integrate risk management into the routine programming and resource allocation processes of the agency. From the asset management perspective, they support multi-objective optimization (Patidar et al 2007).

As presented in Section 2.1, multi-objective asset management is meant to support simultaneously all of the performance goals of the agency, which typically include condition, safety, mobility, and environmental sustainability while minimizing long term cost and managing risk. Risk, in turn, is presented in these Guidelines as uncertainty in achievement of performance objectives.

Among the reasons for framing risk in this way is the potential to combine the concerns about risk, cost, and performance into a relatively simple procedure for priority setting. The types of treatments to be considered in bridge management as a whole include:

- Replacement of bridges, which can improve condition, safety, mobility, and sustainability, and reduce long term cost and risk.
- Functional improvements, which are intended to address safety and mobility deficiencies, and reduce the costs borne by road users.
- Preservation activities, which are intended to improve condition and may reduce risk and long-term cost.
- Risk mitigation activities, which reduce risk and, by doing so, increase the expected value of safety, mobility, and sustainability.

All of these make reference to the same objectives and are funded from the same agency capital budgets, so it has long been considered desirable to prioritize them together. By expressing consequences in economic terms, these Guidelines make it possible to do so.

In a bridge management system, priority-setting and resource allocation are performed according to the ratio of incremental benefits to incremental costs. Each additional unit of possible expenditure is evaluated by estimating the economic value of its increase in network performance (incremental benefit), and dividing this by the change in agency resources that the investment requires (incremental cost). This ratio is often expressed as the IBC:

$$IBC = \frac{\Delta B}{\Delta C} \qquad (27)$$

Where $\Delta B$ is the change in benefit and $\Delta C$ is the change in cost. All modern bridge management systems with resource allocation capability are able to set priorities in this way (Markow and Hyman 2009, Mirzaei et al 2014).

The use of cost, expressed in dollars, in the denominator of equation 27 is important because funding at any given time is limited. Decisions are oriented toward maximizing the amount of total benefit that can be achieved for each dollar spent.

### 4.4.1 Decision making context

The decision-making context determines how these changes in benefit and cost are defined. Two of the principal applications are described in the following sections.

#### *4.4.1.1 Comparison of policies or treatments*

For comparing two alternative policies, or for comparing two alternative courses of action at a given time, an estimate is made of the long-term life cycle activity profiles that follow from each alternative course of action (Hawk 2003). These are expressed as social costs, which are total costs borne by the agency, by road users, and by non-users including the environment. The long-term stream of costs is combined into a single value of social cost using net present value analysis:

$$SC = \sum_{b} \sum_{y=1}^{Y} \frac{SC_{by}}{(1+d)^y} \qquad (28)$$

Where $SC_{by}$ is the total social cost incurred on bridge $b$ in year $y$.

**Discount rate**. In equation 28, $d$ is the discount rate used for inter-temporal tradeoff analysis. The discount rate is determined by agency policy, which should be consistent across all types of assets and all investments of similar lifespan. A common source of guidance is The White House Office of Management and Budget (OMB) Circular A-94 (OMB 2016). Typically inflation is omitted from life cycle cost analyses because this practice simplifies the computations. A riskless and inflationless cost of capital for long-lived investments may use 30-year US Treasury bonds for guidance, with a 2015 real interest rate of 1.5%. Transportation agencies usually specify higher discount rates than this, because of uncertainties in long-term future travel demand and infrastructure requirements. In recent (as of March 2016) Transportation Asset Management Plans, the authors have observed discount rates most commonly in the 1.9% to 2.4% range.

**Analysis period**. Because of discounting of future costs, there are diminishing marginal returns in this analysis. Each additional year added to the analysis period, $Y$, adds less to the total social cost. The analysis period should be long enough, that further extension of the analysis would not significantly affect project selection or resource allocation decisions. In practice, the largest costs in a bridge life cycle are replacement costs, so the analysis period should be at least long enough to encompass one replacement cycle.

As an example to help visualize this effect, if the discount rate is 2% and a typical bridge costs $10 million to replace, the present value of this cost, 50 years in the future, is $10 million × 1 / ((1 + 2%) ^ 50) = $3.72 million, which is still a significant amount of money in comparison to typical preservation costs. If the analysis period is extended to 200 years, the present value is only $190,000. The authors have observed that 200 years is quite commonly used as the analysis period in Transportation Asset Management Plans, for this reason.

**Annual costs**. In the broad framework of capital budgeting, where all types of investments made to existing structures are to be considered, the cost on one bridge $b$ in one year $y$, $SC_{by}$, is made up of multiple components:

$$SC_{by} = \sum_{h}\sum_{c} RC_{byhc} + \sum_{f}\sum_{c} FC_{byfc} + \sum_{a} AC_{bya} \quad (29)$$

The first term, featuring $RC_{byhc}$, is the result of equation 1 and is the main topic of these Guidelines. In the second term, $FC_{byfc}$ is the excess user cost associated with a functional deficiency $f$ affecting a performance criterion $c$. Examples of deficiencies include impaired roadway width, vertical clearance, or load-carrying capacity. This is beyond the scope of these Guidelines but is addressed in references such as Cambridge (2003) and Thompson et al (1999). In the third term, $AC_{bya}$ is the cost incurred by the agency for action $a$ performed on the bridge in year $y$. This can include all types of actions from maintenance to replacement. It can be seen that equation 29 effectively integrates risk assessment fully into the broader scope of asset management.

As noted earlier in these Guidelines, risk costs depend on the likelihood of service disruption and the consequences. Consequences can vary year-by-year because of traffic growth, and they vary from bridge to bridge because of differences in traffic volume and detour length. Likelihood may also vary because of all the factors that go into this computation including location and the effect of time on advanced deterioration and fatigue.

Functional deficiency costs have the same types of user and environmental consequences as in the risk computation, but the likelihood is expressed in terms of the percent of traffic stream affected.

Agency costs vary over time because of deterioration, and from bridge to bridge because of differences in size and complexity.

**Comparing alternatives**. In order to compute benefit, one alternative course of action is typically identified as a base case. By convention, it is called the do-nothing alternative because it involves no immediate expenditure by the agency. Then the incremental benefit cost ratio is

$$IBC = \frac{\Delta B}{\Delta C} = \frac{SC_0 - SC_A}{AC_A - AC_0} \quad (30)$$

Where $SC_A$ is the long-term social cost of alternative $A$ as computed in equation 28; $SC_0$ is the long-term social cost of the do-nothing alternative; $AC_A$ is the near-term agency cost of alternative $A$, and $AC_0$ is the near-term agency cost of the do-nothing alternative. $AC_A$ is the opportunity cost of taking action $A$, the amount of money that is no longer available in the agency's near-term budget for other purposes. Usually $AC_0$ is set by convention to equal zero.

Equation 30 can be used to compare any two alternatives, including a comparison where both alternatives involve near-term expenditures (i.e. neither is do-nothing). In a context with funding constraints, the alternative with greatest IBC is selected. In long-term policy analysis where the amount of funding dedicated to the activity is variable or is to be determined, the cost portion in the denominator is omitted. Then the policy with greatest benefit is selected.

#### *4.4.1.2 Annual programming of work*

For annual programming applications where a set of near-term needs is to be selected within a limited budget, bridge management systems typically simplify the analysis by defining the two alternatives as follows:

- Alternative 1. Do nothing this year, but take the optimal action next year.
- Alternative 2. Take the optimal action (or some user-defined action) this year, then do nothing for some period of time (often 10 years) in the future.

In both cases the optimal action is identified as the course of action which minimizes IBC in equation 30. The incremental benefit in this case is the first year avoidable social cost. If the purpose of an action is to reduce the social costs of safety, mobility, and environmental risks, then a delay of one year in implementing the action will merely cause one additional year of those social costs to be incurred.

For preservation actions, or any actions which are intended to reduce future agency costs, it is necessary to use equation 28 to evaluate agency costs for both alternatives. This is because preservation opportunities are generally available only for structures in relatively good condition. If further deterioration takes place, because of a delay in treatment, the preservation action may become infeasible. This is usually not the case for risk mitigation or functional improvement actions, which remain available at any time to improve performance going forward.

Because of the potential for lost preservation opportunities, the third term of equation 29 is replaced by the difference in life cycle cost between the two alternatives. The treatment of risk costs and functional deficiency costs is simpler because only the first year of consequences is at stake.

### 4.4.2 Decision support

In a bridge management system, the basic priority-setting algorithm represented by equation 30 forms the basis for several aspects of decision support:

**Development of agency policies that minimize life cycle cost.**

It is desirable that such policies be accompanied by an analysis of benefits, including risk benefits, which can assist in the scoping, timing, and prioritization of individual projects.

**Allocation of resources, among performance criteria, among categories of activity, and among jurisdictions.**

If a list of candidate investments is prioritized as discussed in the preceding section, then the amount of money spent on each subset of projects defines a possible allocation of resources.

**Evaluation of outcomes.**

Bridge management systems use deterioration models and other tools to forecast future performance, taking into account all the investments that can be implemented each year within funding constraints. The combined effect is a forecast of fiscally-constrained network performance outcomes. Any set of candidate investments, whether economically optimal or not, can be evaluated in this way to estimate resource allocations and performance outcomes. Agencies typically employ managerial and political discretion toward the goal that an acceptable set of outcomes is produced, taking into account all relevant economic and non-economic factors.

**Establishment of performance targets.**

Federal rules following from 23 USC 119 mandate that agencies adopt a set of performance targets for condition, and also adopt a process leading to the achievement of the full set of federal goals including safety, mobility, and environmental sustainability. For the risk-related aspects of performance, the utility or resilience measure defined in equations 3-5 can be used in the same manner that condition is used in the federal rules. Resilience can be discretized into Good, Fair, and Poor levels, and fiscally-constrained targets can be set for the percent of deck area on bridges classified as having Good or Poor resilience.

Realistic performance targets are necessarily constrained by funding. Gaining an understanding of the funding vs. performance relationship is central to any fully-informed discussion of funding alternatives. The tools described here can help decision makers to gain a useful intuition for this relationship. Figure 15 is an example illustrating the tradeoff.

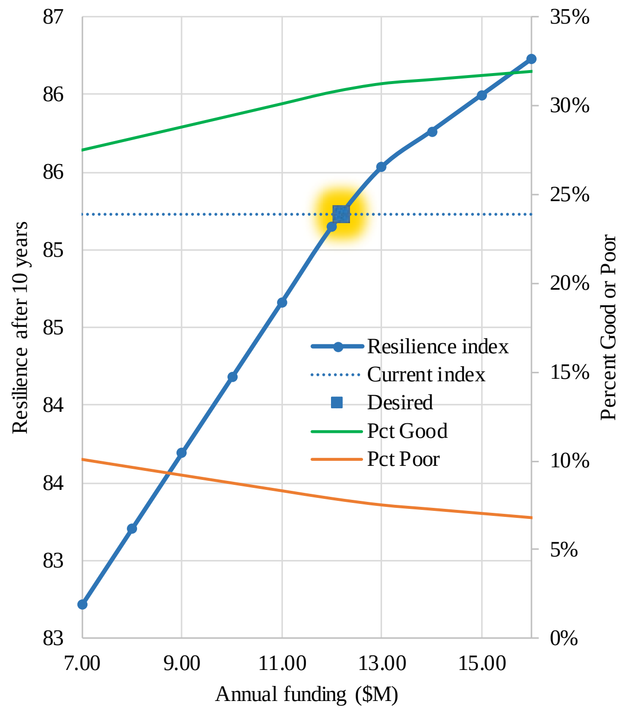


*Figure 15. Funding vs performance tradeoff*

# 5. Incorporating risk in bridge management systems

This chapter addresses some related subjects in more detail, to support the tools described in the previous chapters. They help to describe the context in which these Guidelines were prepared.

## 5.1 Established risk assessment tools

The following sections describe existing approaches used by some leading agencies in their efforts to support risk-based decision making. Many aspects of these approaches were adopted in the preparation of these Guidelines.

### 5.1.1 Florida DOT Project Level Analysis Tool (PLAT)

Florida DOT implements the products of its bridge management research in the Project Level Analysis Tool (PLAT, Sobanjo and Thompson 2013), an Excel spreadsheet model built on the AASHTOWare Pontis database to analyze the performance of any one selected bridge. The PLAT, in turn, contributes estimates of cost and effects to the Network Analysis Tool (NAT), a separate spreadsheet model which is used for priority setting and programming of bridge work on a district and statewide basis.

Philosophically, the performance management approach taken in the PLAT and NAT is to attempt to quantify all costs and benefits in dollar terms at the project and network levels. Each project may affect transportation system performance in a variety of ways: initial cost, life cycle cost, safety, mobility, and risk. These project benefits are considered together in a multi-objective optimization framework. In the FDOT models, the utility function for this multi-objective framework is social cost, consisting of agency, user, and non-user costs.

A variety of bad things can happen to good bridges in Florida: hurricanes, tornadoes, wildfires, floods, collisions, advanced deterioration, and fatigue. The causes are, at least in part, outside agency control and subject to random external factors. They are considered to be hazards, which are quantified in terms of the likelihood of a hazard event. All of these hazards can cause a bridge to be damaged or destroyed, delivering a consequence to the agency (the cost to repair or replace the structure) and an impact on the public (disruption of transportation service and of the larger economy). Figure 16 shows the basic ingredients.

Hazards are modeled probabilistically. At a given bridge site, the hazard can strike with various levels of severity that can be forecast only with a broad concept of probability distribution. An F2 tornado 500 feet wide may touch down near a bridge, pass 1000 feet from the structure, and do no damage. The same tornado with stronger winds or a slight variation in its path may destroy the same bridge. Tornadoes can happen anywhere in Florida, and do occasionally damage bridges. It is impossible to forecast future events on one given bridge, but it is possible to quantify a general level of risk based on regional records of tornado occurrence and statewide tornado damage.

Once a hazard strikes, the damage to the structure and impact on the public are also probabilistic, subject to a limited degree of agency control. A wildfire near a bridge may engulf and destroy the structure, or may cause varying levels of repairable damage, or may spare the structure and merely disrupt traffic with a pall of smoke. Efforts by emergency crews to save the structure or to minimize the impact on traffic have varying effectiveness, depending on random factors. When a hurricane strikes, the Department may close bridges pre-emptively to protect life, even if the bridge is not ultimately damaged.

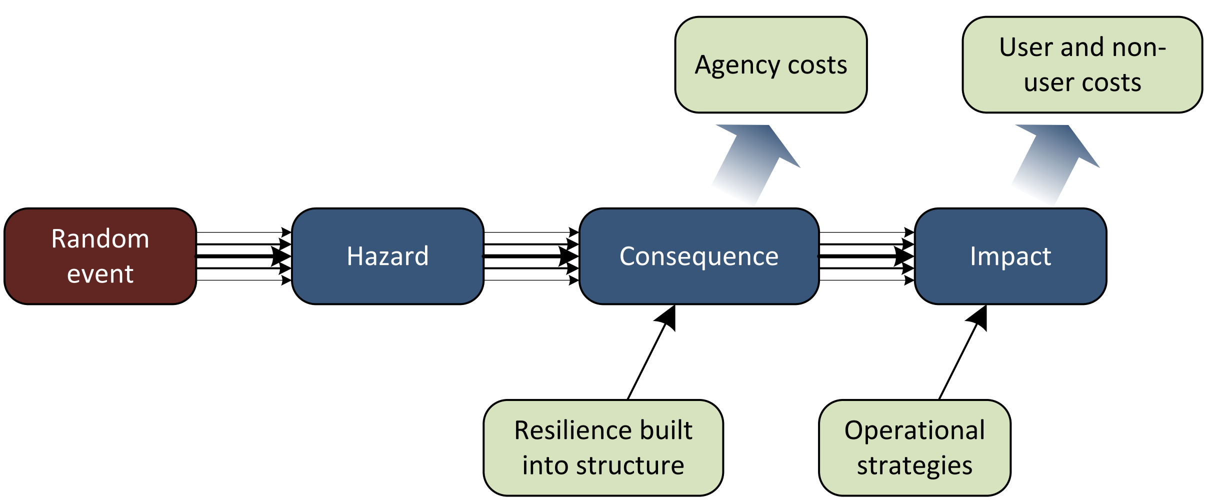


*Figure 16. Basic ingredients of risk analysis in PLAT (Sobanjo and Thompson 2013). Colors distinguish inputs from results.*

For bridge management purposes, the main decision variable in the Florida risk analysis is the selection and timing of programmed actions to increase the resilience of the Department's structures, thus indirectly influencing the social costs caused by hazards. The controllable costs of structure resilience and operational strategies are combined with the more random future outputs of agency, user, and non-user costs due to hazard events, to produce forecasts of life cycle costs. In effect, the programmed and consequential costs of risk are included within the life cycle cost analysis.

In order to place a dollar value on hazard consequences, regional or statewide historical records of hazards and their dollar-valued recovery costs were summarized and used as a gross indication of future risk. This risk is allocated to specific bridges in a way that is reflective of structure resilience and significance. A bridge is assigned more risk if it has a higher probability of an adverse event, if it has less resilience, if it is expensive to replace, or if it is used by a large number of people.

For natural hazards, the probability of an adverse event in most cases is developed from geographically-referenced hazard maps maintained by the state and federal governments. Specialized statistical models were developed for the likelihood of fuel truck collisions, overloads, over-height collisions, advanced deterioration, and fatigue. Resilience in most cases was based on data already available in the FDOT Pontis database, such as structure type, scour assessment, and condition.

Using this perspective, risk is spread in a consistent manner among bridges, and from year to year over time. Risk may gradually increase over time because of traffic growth and deterioration. If a risk mitigation or replacement action takes place, resilience improves and risk is reduced for the time subsequent to the action (Figure 17). The life cycle cost (LCC) of this scenario is the sum of discounted social costs incurred throughout the life of the crossing served by the bridge. Risk-related costs are high without the mitigation action, and lower once the action is applied. The action itself also has a cost. If the life cycle that includes the action has lower total LCC than a life cycle without the action, then it is attractive to perform the work.

For project selection purposes in any given year, LCC can be computed for a variety of feasible actions, including doing nothing, to select the action which minimizes LCC. The total benefit of a project is the savings in LCC relative to doing nothing.

If a project is delayed, this lengthens the period of higher risk costs, and thus increases LCC. The benefit of accelerating a project by one year is the one-year savings in life cycle cost. In a priority programming context where a limited budget must be allocated among projects each year, the best projects are those which would save the most in risk costs, relative to each dollar spent, if they are done this year rather than waiting another year.

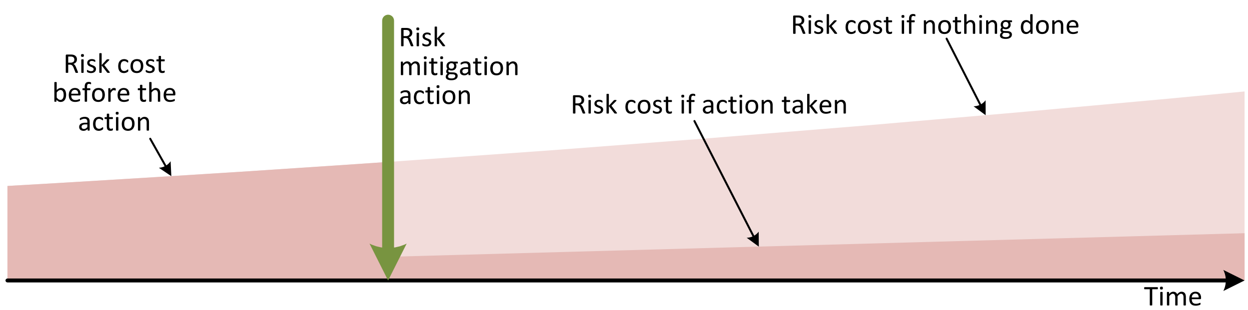


*Figure 17. Life cycle activity profile for risk (Sobanjo and Thompson 2013)*

## 5.1.2 Minnesota DOT Bridge Replacement and Improvement Management (BRIM)

Minnesota DOT uses a risk-based prioritization tool, developed as an Excel spreadsheet called BRIM, to identify and rank most of the bridge projects that are submitted for its Statewide Transportation Improvement Program (STIP) (Thompson et al 2012). Unlike the AASHTO and Florida methods, BRIM does not develop separate estimates of likelihood and consequence of an event. Instead, it uses a set of rating tables to convert directly from bridge characteristics in its Pontis database to a measure of utility which it calls the Bridge Performance Index (BPI). These tables were developed entirely from judgment.

Figure 18 shows the conversion from superstructure condition to BPI. In this table, a smart flag reduction can be triggered by smart flags such as pack rust, section loss, and concrete shear cracking, or by unusual conditions of certain elements such as cables and hinges. Similar tables exist also for decks and substructures.

Figure 19 shows the table for scour. Minnesota, like many other states, uses a scour classification system that is more detailed than Federal standards. The BPI is reduced if certain smart flags are present. Similar tables were also developed for fracture criticality, fatigue, overweight trucks, over-height trucks, driver loss of control, and overtopping of the bridge or approach.

Since the BPI scores are based entirely on bridge characteristics, they are also a measure of resilience in the same sense as in the Florida system. That is, they represent bridge qualities that the agency controls, that it spends money to improve over time, that reduce the likelihood of transportation service disruption. The BPI score does not consider the site-specific likelihood of adverse natural events such as earthquakes or floods.

In order to use the BPI score for priority-setting, BRIM further adjusts the BPI by moving scores within the 0-100 range based on traffic volume, bridge length, detour length, and network class. The BPI score is used directly for prioritization, without considering project cost or long-term cost, making it a true worst-first framework.

| | | SUPERSTRUCTURE CONDITION | | |
|---|---|---|---|---|
| | | Smart flag reduction | | |
| NBI Condition | | None | Case 1 | Case 2 |
| N | Not applicable | 100 | 100 | 100 |
| 9 | Excellent | 100 | 90 | 80 |
| 8 | Very good | 95 | 85 | 80 |
| 7 | Good | 90 | 80 | 60 |
| 6 | Satisfactory | 75 | 60 | 40 |
| 5 | Fair | 55 | 40 | 25 |
| 4 | Poor | 35 | 25 | 10 |
| 3 | Serious | 15 | 10 | 0 |
| 2 | Critical | 5 | 5 | 0 |
| 1 | Imminent fail | 0 | 0 | 0 |
| 0 | Failed | 0 | 0 | 0 |

*Figure 18. BPI table for superstructure condition (Thompson et al 2012). Colors distinguish ranges of BPI.*

| | | SCOUR | | | |
|---|---|---|---|---|---|
| | | Smart flag reduction | | | |
| Code | Description | None | 1 | 2 | 3 |
| A | Not a waterway | 100 | 100 | 100 | 100 |
| E | Culvert | 100 | 100 | 100 | 100 |
| M | Stable; scour above footing | 90 | 90 | 70 | 40 |
| H | Foundation above water | 90 | 90 | 70 | 40 |
| N | Stable; scour in footing/pile | 80 | 80 | 60 | 30 |
| I | Screened; low risk | 70 | 70 | 50 | 30 |
| L | Evaluated; stable | 70 | 70 | 50 | 30 |
| P | Stable due to protection | 60 | 60 | 40 | 20 |
| K | Screened; limited risk | 60 | 60 | 30 | 20 |
| F | No eval; foundation known | 50 | 50 | 40 | 20 |
| C | Closed; no scour | 50 | 50 | 25 | 20 |
| J | Screened; susceptible | 40 | 40 | 30 | 10 |
| O | Stable; action required | 40 | 40 | 20 | 10 |
| G | No eval; foundation unknown | 20 | 20 | 15 | 10 |
| R | Critical; monitor | 10 | 10 | 5 | 0 |
| B | Closed; scour | 0 | 0 | 0 | 0 |
| D | Imminent protection reqd | 0 | 0 | 0 | 0 |
| U | Critical; protection required | 0 | 0 | 0 | 0 |

*Figure 19. BPI table for scour (Thompson et al 2012). Colors distinguish ranges of BPI.*

## 5.1.3 New York State DOT Bridge Safety Assurance Program

New York State DOT has adopted a third approach, based on a system of decision trees, to compute a priority indicator that it calls Vulnerability Rating (NYSDOT 2013). As is the case with Minnesota's BPI, New York's indicator is derived from bridge characteristics, but New York separately computes the likelihood and consequence of structural damage (Figure 20). New York's method of estimating extreme event likelihood is based on research, like Florida's.

New York's vulnerability rating can be understood as the opposite of the Florida resilience concept, except it is somewhat broader since it includes extreme event likelihood and, to a small extent, traffic volume. It has a limited scale where 0 is best and 20 is worst (Figure 21). NYSDOT uses the vulnerability rating for priority-setting within the safety assurance program, without considering project costs or long-term costs.

| | | | |
|---|---|---|---|
| **Likelihood score** | | | |
| Vulnerability class | | | |
| High | = | 10 | |
| Medium | = | 6 | |
| Low | = | 2 | |
| Not vulnerable | = | 0 | |
| **Consequence score** | | | |
| Failure type | | | |
| Catastrophic | = | 5 | |
| Partial collapse | = | 3 | |
| Structural damage | = | 1 | |
| Exposure - Traffic volume score | | | |
| > 25,000 AADT | = | 2 | |
| 4,000 - 25,000 AADT | = | 1 | |
| < 4,000 AADT | = | 0 | |
| Exposure - Functional classification score | | | |
| Interstate and freeway | = | 3 | |
| Arterial | = | 2 | |
| Collector | = | 1 | |
| Local road and below | = | 0 | |
| **Total** | | | |
| Vulnerability rating | | | |

*Figure 21. Calculation of the vulnerability rating (NYSDOT 2013)*

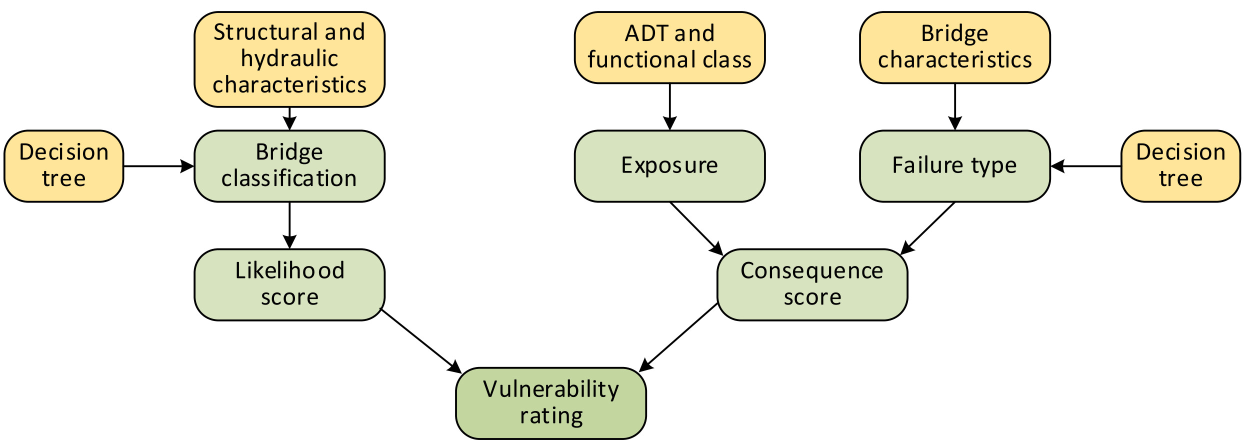


*Figure 20. Calculation of vulnerability rating (adapted from NYSDOT 2013). Colors distinguish inputs from results.*

### 5.1.4 Federal Sufficiency Rating

A far older version of the same philosophy used in New York is embodied in the National Bridge Inventory (NBI) Sufficiency Rating (SR), which was developed in the 1970s and has been a cornerstone of federal management of the national bridge program ever since (FHWA 1995). The SR formula can be understood as a proxy for the unknown likelihood of service disruption. The SR is calculated on a scale of 0 (worst) to 100 (best), with the following components:

55% of the rating:
Condition (deck, superstructure, and substructure ratings)
Load-carrying capacity (inventory rating and its impact on mobility)

35% of the rating:
Geometrics (lane width, clearances, alignment; affecting mobility and over-height truck hazard)
Condition and load-carrying capacity (additional weight to represent overweight truck hazard)
Waterway adequacy (resistance to scour and overtopping hazards)

15% of the rating:
Essentiality for public use (changes the relative weights given to the above factors based on traffic volume and network importance)

Up to 13% reduction for:
Special safety and mobility deficiencies (increases bridge priority to account for especially long detour routes or substandard safety features, affecting a relatively small fraction of bridges)

The SR does not consider likelihood of natural extreme events, and contains very minimal consideration of traffic volume. As a result, it is very similar to the resilience concepts used in Florida and Minnesota. It was used for priority-setting in the early days of the bridge program, but was not well-suited for benefit/cost analysis since it disadvantaged the large structures which cost more to repair and replace. It is still used in some states as a performance measure, however.

## 5.2 Methodology in AASHTOWare Bridge Management

The methods described in these Guidelines have, as one objective, the ability to be implemented within AASHTOWare Bridge Management (BrM), which, as the successor to Pontis, is likely to be the most widely-used bridge management system. BrM is still under development and does not yet have the capability to execute the methodology described here. However, design documentation provided to the AASHTO member agencies, if fully implemented, will have the necessary functionality in release 5.2.3.

In addition to the capabilities represented by equations 1 through 5 in Section 3.2.3, BrM has some additional requirements, in particular:

- Agencies need to be able to add data items to support the risk assessments they choose, and calculate performance measures from these items.
- Agencies should be able to define and prioritize projects consisting of multiple bridges, where each bridge has its own set of needs.
- Agencies should be able to manipulate the relative weights given to different performance concerns at the program level, to gain an understanding of the relative tradeoffs of concentrating investments in different types of projects.
- For speed and responsiveness, the calculation of social cost used in the program level analysis should be based on the utility calculation made for each individual work candidate. It should not be necessary to re-analyze every work candidate if project composition, budget constraints or relative weights are changed.

The following capabilities described in the system design documentation are necessary in order to support the computations described in these guidelines:

- Ability for utility formulas and performance measures to access the Assessments data and the agency-defined tables of the database (such as USERBRDG and USERINSP), where many agencies store scour classification data, seismic zone, and other important information for risk management.
- Tables for agency-defined configuration parameters (PON_MOD_PARAM) and performance measure definitions (PON_MOD_PERFORMANCE), with access to these tables from the formulas used in configuring performance measures and utility functions.
- The ability to store utility or vulnerability separately by performance criterion in each work candidate (PON_ACT_PERFORMANCE and PON_WK_PERF_FORECAST tables). These should be stored in unweighted form so criterion weights and structure weights (which may be manipulated by the user) can easily be applied in the program level analysis.
- The use of structure weights (in the PON_BRIDGE_WEIGHT and PON_SCENARIO_PERF tables) to compute network-level project benefits and to reflect the bridge's importance in the network, or its effect on network-wide performance. This is essential for using a utility framework in a benefit/cost analysis, since larger bridges tend to cost more and also tend to have a greater impact on network performance. A large bridge would be disadvantaged in a benefit/cost priority ranking unless this scale of effect on the network is taken into account. The weighting method is designed to vary by performance measure.
- There may be additional formula writing capabilities that would be valuable to facilitate the definition of appropriate utility functions. For example, the formula editor currently is limited to single mathematical expressions. The likelihood functions for advanced deterioration and fatigue use probability distribution calculations. It is possible that some of the computations needed for risk analysis may be too complex for the simple capability provided.

## 5.3 Computation of recovery costs

The computation of recovery costs can be a complex process, as costs can vary depending upon location, type of bridge, length of bridge, etc.  Therefore, a universally accepted practice for estimating the cost of a bridge replacement project for planning purposes would be to compute a cost per square foot.  These costs could only be used for planning purposes, and would require a complete engineering estimate and would require a complete engineering estimate prior to design.

The Florida Department of Transportation (FDOT 2014) compiled a reference list of square foot costs for various bridge types using historical data from recent bridge replacement projects (see Table 15).  States could create their own similar tables using unique data from recent projects, or could use this table assuming costs are similar.  As a rule of thumb, Short Span Bridges are defined as being 20-45 feet in length, Medium Span Bridges are 45-150 feet in length, and Long Span are greater than 150 feet.

*Table 15: Cost Per Square Foot New Construction Costs (FDOT)*

## New Construction
(Cost per Square Foot)

| Bridge Type | Low | High |
|---|---|---|
| **Short Span Bridges:** | | |
| Reinforced Concrete Flat Slab Simple Span* | $115 | $160 |
| Pre-cast Concrete Slab Simple Span* | $110 | $200 |
| Reinforced Concrete Flat Slab Continuous Span* | NA | NA |
| **Medium and Long Span Bridges:** | | |
| Concrete Deck/ Steel Girder - Simple Span* | $125 | $142 |
| Concrete Deck/ Steel Girder - Continuous Span* | $135 | $170 |
| Concrete Deck/ Pre-stressed Girder - Simple Span | $90 | $145 |
| Concrete Deck/ Pre-stressed Girder - Continuous Span | $95 | $211 |
| Concrete Deck/ Steel Box Girder – Span Range from 150' to 280' (for curvature, add a 15% premium) | $140 | $180 |
| Segmental Concrete Box Girders - Cantilever Construction, Span Range from 150' to 280' | $140 | $160 |
| Movable Bridge - Bascule Spans and Piers | $1,800 | $2,000 |
| * Increase the cost by twenty percent for phased construction. | | |

## Bridge Demolition and Widening
(Cost per Square Foot)

| **Bridge Demolition:** | Low | High |
|---|---|---|
| Typical Bridge Removal | $35 | $60 |
| Movable Span Bridge (Bascule) | $60 | $70 |
| **Widening:** | | |
| Bridge Widening Construction | $85 | $160 |

# 6. Future research needs

These Guidelines were developed under the current state of industry knowledge of hazards and performance. Risk represents the cutting edge of performance uncertainty, so further research into these issues is itself a risk reduction activity. In these guidelines a number of potentially fruitful areas of future research were identified:

- There is no comprehensive reference, similar to these Guidelines, for identifying appropriate risk mitigation treatments, establishing warrant criteria, and for estimating treatment cost and effectiveness. Development of such a document would be a logical next step. The work would likely require a survey of the states and an in-depth examination of methods and project histories from a selection of states.
- For many common hazards, there is considerable anecdotal evidence of damage and service disruptions from adverse events, but this information is in fragmented sources that have not been brought together for the purpose of a bridge management risk assessment. A national-scale effort could compile this information and provide a stronger risk allocation calculation than any individual state could accomplish by itself. The work described in Stein and Sedmera (2006) for scour is a good example.
- While many agencies are likely to implement these guidelines within AASHTOWare Bridge Management, there are certainly many other potential applications of the risk analysis for more specialized purposes such as site-specific studies, policy analysis, and development of mitigation programs. There may be enough of these applications to justify the development of a stand-alone spreadsheet application that implements these Guidelines. The advantage of a spreadsheet application for this purpose is that it could readily be modified by agencies and consultants to match the special needs of each agency.
- The quantification of environmental sustainability consequences in these Guidelines can be improved by considering carbon dioxide emissions and by modeling the effects of hazard scenarios on water, agricultural, recreational, and cultural resources.
- Some initial work has been done on the assessment of bridge structural characteristics in relation to damage and disruption due to storm surge and tsunami (Sobanjo and Thompson 2013), but this could be improved by the systematic examination of storms from multiple states. In addition, there has been recent work on geographically-referenced forecasting of sea level rise, which needs to be associated with bridge and site characteristics to improve the estimates of likelihood of service disruption.
- There is substantial room for improvement in the ability to quantify the relationship between scour and flood characteristics and the likelihood of service disruption. The methods described in this guide depend primarily on NBI data and might be improved by means of a field assessment of the most significant variables in the structural response.
- Over-height truck collisions are quite common and can cause a wide range of disruptions depending on the characteristics of the impacted bridge. There is potential for research to develop a field assessment of bridge characteristics, and corresponding disruption likelihood and consequence models, that estimate the duration and severity of such collision events.
- Related to the previous need, there is a need for research on the effectiveness of mitigation strategies related to overload and over-height hazards. These measures might include enforcement strategies, sensors, portal frames, and signage. These results should be integrated with the field assessment so their use can influence the estimates of disruption likelihood and consequences.
- Florida DOT research (Sobanjo and Thompson 2013) found that advanced deterioration was, by far, the biggest contributor to bridge risk in its inventory. The research developed a lognormal model to aid in forecasting this hazard. Given its importance, further research would be justified to analyze other state inventories and to relate the likelihood of service disruption to the new data available under the 2013 AASHTO Guide for Bridge Element Inspection.
- Individual agencies may wish to research the extreme event likelihood of natural hazards most affecting them. In some cases, such as wildfires, this may involve creating new geographic resources (fuel availability maps) that do not yet exist in the state. In other cases, it may involve cleanup and mining of existing geographic databases. Flood and landslide databases, in particular, are subject to changing conditions where frequent updates can improve data quality.
- Agencies having bridges over significant navigable waters may want to research the influence of vessel and waterway characteristics on the likelihood and consequences of vessel collisions. The available information is fragmented and would require some further manipulation and data collection to maximize its usefulness in a BMS risk assessment.

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