RISK ASSESSMENT FOR BRIDGE MANAGEMENT SYSTEMS

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ABSTRACT
National Cooperative Highway Research Program (NCHRP) Project 20-07, Task 378 was commissioned by the American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Bridges and Structures to develop a Guideline for Risk Assessment for Bridge Management Systems, to be used within a bridge management system (BMS) to estimate the beneficial effects of bridge risk mitigation and replacement on transportation performance, as a part of methods for project utility and benefit/cost analysis. AASHTOWare Bridge Management was explicitly targeted, but the methodology is intended to be usable with any BMS using the data typically collected by, or available to, US highway agencies.

The final Guideline, now complete and due to be published in early 2017, describes methods for developing service disruption scenarios, and then estimating the likelihood and consequences of these scenarios. Likelihood probability models are provided for 16 hazards including earthquake, landslide, storm surge, high wind, flood, scour, wildfire, temperature extremes, permafrost instability, overload, over-height collision, truck collision, vessel collision, sabotage, advanced deterioration, and fatigue. Consequences of service disruption are estimated in dollars for recovery cost, safety, mobility, and environmental sustainability. All of these models are based on published research gathered from a wide variety of sources, and consistent with the AASHTO Guide for User and Non-User Benefit Analysis for Highways (the "Red Book").

The economic basis for risk assessment is designed to be compatible with existing use of life cycle cost analysis in BMS, as well as with the utility framework provided in AASHTOWare Bridge Management. This paper introduces the methodology to inform the bridge management community of the new resource soon to be available.

Keywords: Bridges, Structures, Risk, Hazards, Safety, Mobility, Sustainability

INTRODUCTION

Transportation Asset Management uses data and analysis to improve decision making, with the goal of providing the desired level of service in the most cost-effective manner. A Bridge Management System (BMS) contains features to apply bridge inventory and condition data to assess the costs and benefits of preservation, risk mitigation, and replacement activities, to support management decision making processes such as project definition, priority setting, resource allocation, and programming.

BMS have long had functionality to estimate the effects of agency actions on the long-term cost of maintaining the desired level of service. Recent BMS innovations have opened the door to multi-objective assessment of additional stakeholder concerns including safety, mobility, and environmental sustainability (*1*). Bridges affect these concerns by means of their functional characteristics, and by means of the risk that natural or man-made hazards might disrupt transportation service.

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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 1). 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.

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. Given a list of selected projects in a fiscally-constrained program, the BMS estimates future network condition and performance outcomes. Such estimates can be used for evaluating and comparing program alternatives, and for establishing performance targets and resource allocations.

Most fully-developed bridge management systems compute project benefits using a life cycle cost analysis, as depicted in Figure 1. 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 model to accompany the life cycle cost analysis in computing project benefits. The risk assessment uses information about the project and the effects of the project on future bridge characteristics, to compute a portion of the project benefit.

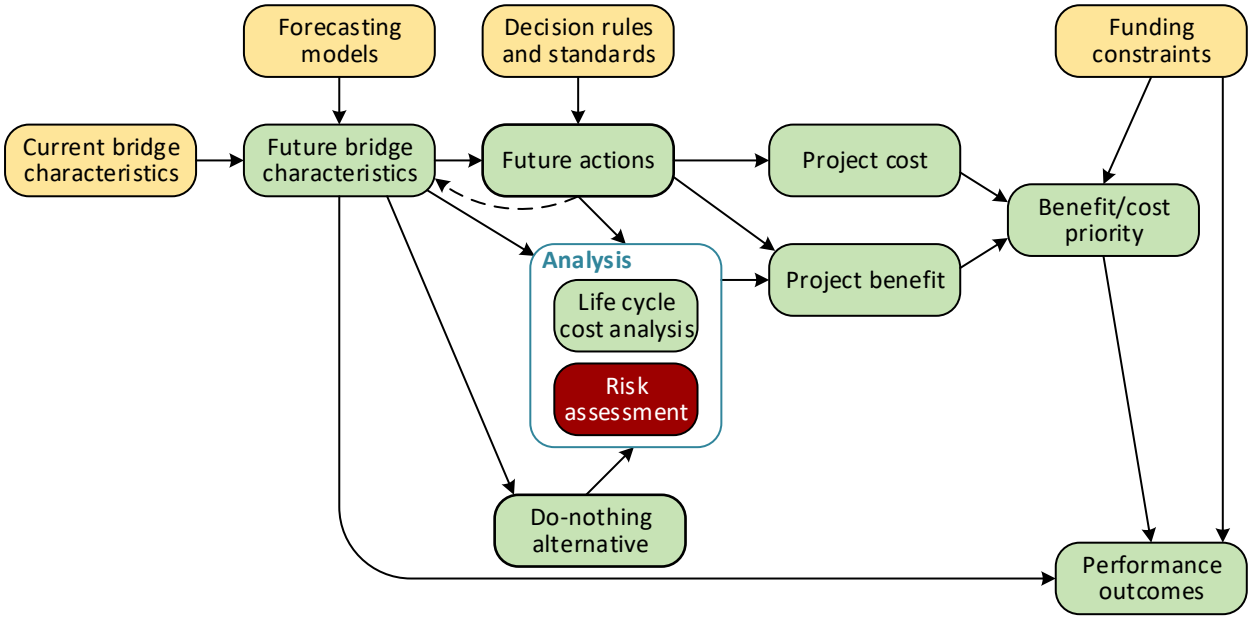

FIGURE 1 Role of risk in a bridge management system framework.

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):

Safety
Infrastructure condition

Congestion reduction
System reliability
Freight movement and economic vitality
Environmental sustainability
Reduced project delivery delays

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 and manage risks. Each state DOT typically has a similar list of goals. In bridge management decision making, the most relevant concerns are cost, safety, mobility, and environmental sustainability, with condition and risk potentially influencing all of the other goals.

When conditions of individual bridges are compared with each other, or when one bridge is tracked over time, it is common practice to use a bridge health index (*2*) or a good-fair-poor classification as in recent federal rules (23 CFR 490). To characterize risk on a comparable basis, it is possible to use a concept of resilience or vulnerability (*3*). Network conditions or resilience can be characterized as the percent good or percent poor, perhaps weighted by deck area as in the federal rules.

For benefit/cost priority-setting, it is necessary to describe performance of the network as affected by a given bridge. Cost varies from one bridge to another based on size and potentially other factors. Risk mitigation benefits also vary from bridge to bridge because of traffic volume, detour length, and potentially other factors. NCHRP Report 590 explores ways of combining safety, mobility, and other project benefits, taking traffic and detour length into account, to estimate project benefits as a type of utility function (*1*). As an alternative, it is possible to estimate project benefits in the form of user costs, as is done in Florida DOT's analytical process (*4*). This latter approach simplifies the means of combining risk benefits with life cycle cost reduction. The Guideline described in this paper supports both methods.

OVERALL FRAMEWORK

The Guideline presents the risk assessment procedure as 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 "mix and match," to plug in the modules which best fit their needs (Figure 2). Depending on the hazards to be addressed, the agency will choose among plug-in modules for the likelihood of extreme events, the likelihood of service disruption, and the consequences of service disruption. The agency defines a set of hazard scenarios and applies the

modular analysis to compute social cost and/or utility for use in the priority-setting and resource allocation functions of the BMS.

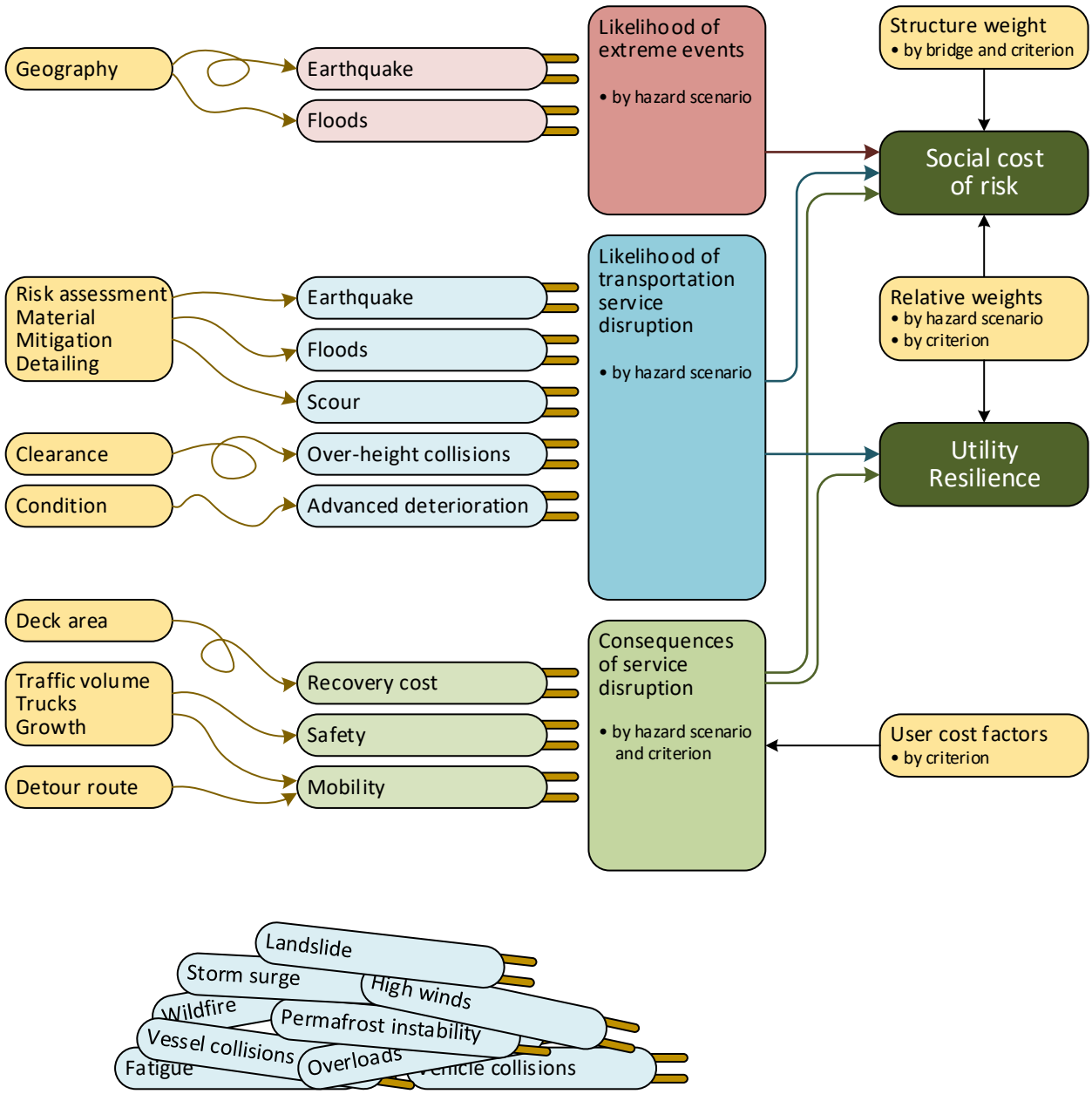

FIGURE 2 Plug-in architecture of the recommended risk analysis

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), or the cumulative effect of an ongoing adverse process, 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 cost, safety, mobility, and environmental sustainability.

Each agency will select the hazard scenarios and performance criteria to be analyzed consistently across all bridges. 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 is 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.

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

- 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 at least once every 100 years for a given bridge.
- 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.
- 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.
- 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?
- 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 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 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.

Project Summary Worksheet

Figure 3 shows the Project Summary Worksheet, presenting intermediate and final results of the risk calculations for a single bridge and project as developed in the Guideline. Input data requirements are provided in the upper two blocks of cells.

The lower two blocks of cells are calculation results. Green cells are results, in thousands of dollars, gathered from worksheets provided for each type of consequences. Red cells are extreme event probabilities gathered from worksheets for each type of hazard scenario. Blue cells are service disruption probabilities gathered from worksheets for each type of hazard scenario. Gray cells are configuration parameters set on a separate worksheet. White cells in the lower two blocks are calculated on the worksheet itself.

NCHRP 20-07 (378) Risk Analysis

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 ($000)				Likelihood			Risk
ID	Scenario	Cost	Safety	Mobility	Environment	Extreme	Disruption	Weight	Cost ($k)
1	Earthquake-100	12,345	50	6,000	600	1.00%	5.00%	1.00	9.50
2	Flood 100a	12,345	50	6,000	600	1.00%	10.00%	1.00	19.00
3	Flood 100b	100	0	2,000	200	1.00%	20.00%	1.00	4.60
4	Flood 500	12,345	50	6,000	600	0.20%	50.00%	1.00	19.00
5	Overheight	100	70	200	40	--	5.00%	1.00	20.50
6	Deterioration	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

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
Risk cost ($k)	102.79	3.63	79.00	10.90
Vulnerability	5.1394	0.0483	0.5878	0.0811

Risk analysis results	
Maximum unit risk cost:	100.00
Vulnerability index:	0.0586
Utility:	**94.14**
Social cost of risk ($000):	**196.31**

FIGURE 3 Project Summary Worksheet

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. It has two parts:

LE_{bh} = likelihood of occurrence of the extreme event of given magnitude that is specified by hazard scenario *h*, estimated for bridge *b*.

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*.

The total likelihood of hazard scenario *h* on bridge *b* is $LE_{bh} \times LD_{bh}$. The two likelihood estimates are separated because different data sources and methods are used to calculate them, as described below. These likelihoods are the probability of the indicated event occurring in any one year. Agencies using AASHTOWare Bridge Management may want to use the Assessments feature of that system as a basis for estimating one or both of the likelihoods.

Consequences of service disruption
Consequences are defined as an economic quantity, that varies by bridge, based on bridge and network characteristics. It also varies by hazard scenario and performance criterion.

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.

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 recovery cost is typically estimated using economic models and normal agency cost estimation practices, or by classifying potential losses in ranges using judgment. Methods for other types of consequences are described below.

Performance measures
The basic ingredients described in the preceding section are used 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. 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. Its values can range from 0 to 100, where 0 is the worst possible performance and 100 is the best possible performance.

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.

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. It is equivalent to resilience. 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. By definition, 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. 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.)	
Safety	Average daily traffic (ADT)	
Mobility	ADT × Detour length (miles)	(6)
Environmental sustainability	ADT × Detour length (miles)	

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.

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.

SUBMODEL EXAMPLES

The following sections provide examples of the modules documented in the Guideline for likelihood of extreme events, likelihood of service disruption, and consequences of service disruption. The study collected methods from existing literature and did not have resources to develop new methods. There are significant opportunities for future research to develop new and better methods for many of the hazards and criteria that can be assessed within this framework.

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.

Natural extreme events

For a given agency, geographically-referenced data on extreme event likelihood may be available from several sources. 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.

As an example, the U.S. Geological Survey (USGS) National Seismic Hazard Maps (Figure 4) display earthquake ground motions for various probability levels across the United States. They represent a uniform probability (either 2% or 10%) that the ground acceleration will exceed the given value over 50 years. These can translate directly to an event likelihood for a corresponding hazard scenario. FEMA, NOAA, USFS, and various state agencies are potential sources of geographic hazard data.

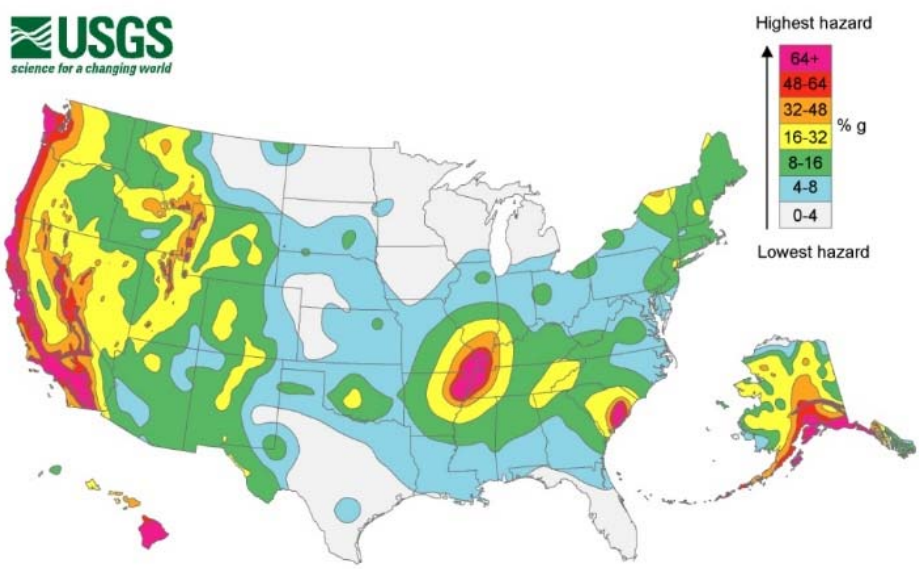

FIGURE 4 USGS National Seismic Hazard Map

Man-made extreme events

The Guideline also provides suggested methods for gathering incident data that might be used for human-caused extreme events such as overloads, over-height truck or tanker truck collisions, vessel collisions, and sabotage. In some cases existing data sources can be used to gain insight

into the overall statewide probability of some of these hazards, which can form the basis for individual site estimates.

Likelihood of service disruption

For hazard classes that involve extreme events, the likelihood of service disruption is the probability that service is impacted, conditional on the occurrence of the related extreme event scenario. While the extreme event probability depends mainly on location or other exogenous factors, the service disruption probability typically depends on structure characteristics. Certain hazards, such as advanced deterioration, are not associated with extreme events but have service disruption probabilities (e.g. restricted load ratings requiring posting) that depend only on structure characteristics. Models are provided for the following hazards:

Earthquake	Wildfire	Vessel collision
Landslide	Temperature extremes	Sabotage
Storm surge	Permafrost instability	Advanced deterioration
High wind or tornado	Overload	Fatigue
Flood	Over-height collision	
Scour	Tanker truck collision	

The Guideline presents worksheets and examples for several generic methods to approximate the disruption probability, that can be applied to most hazard classes even with minimal data availability. For example:

- Assessments. Using the AASHTOWare Bridge Management feature for risk assessments, a probability is assigned to each likelihood category based on judgment, derived perhaps from a Delphi or Analytic Hierarchy process.
- Scoring tables or decision trees. A set of objective criteria, using BMS data items, are used to group bridges into categories of vulnerability, then those categories are scored and converted to a probability.
- Analogies. Using a Delphi-type process to lead a panel of experts to a likelihood estimate based on comparisons with other hazards having known frequencies.
- Polling. Asking a group of knowledgeable individuals (e.g. area maintenance supervisors) to list past incidents from memory, and/or to estimate the frequency of such incidents. This can also be used to estimate other needed parameters such as extent of damage and length of closure.
- Risk allocation. Use statewide expenditures, news reports, polling of maintenance personnel, and other historical data to estimate the total damage and disruption statewide. These totals are scaled for network growth and inflation, then allocated among bridges to reflect bridge characteristics that make each structure more or less vulnerable.

These methods can be used separately or in combination, exploiting whatever data the agency can locate, to bracket reasonable risk estimates for each hazard class. Table 1, for example, is

adapted from a scoring table used by Minnesota DOT (*5*) to set the relative likelihood of service disruption based on a field-assessed scour rating. It can be used in combination with statewide frequency estimates to compute a probability for each bridge using the risk allocation method.

The Guideline also documents methods developed from past research studies that are specific to certain hazard classes, most notably for scour, overloads, over-height collisions, tanker truck collisions, terrorism, advanced deterioration, and fatigue. In some cases, such as scour, multiple alternative models can be found in the literature. For example, New York State DOT has its own scour decision tree model (*3*), and an NCHRP study developed a risk allocation model for scour based on national datasets (*6*).

TABLE 1 Scoring table for scour (adapted from Minnesota DOT)

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
Defect reduction:					
Use worst condition state of defect 6000, Scour					

Consequences of service disruption

The framework used in the Guideline relies on the clear definition of service disruption scenarios to formulate the likelihood × consequence concept of risk in a way that can reasonably be estimated using quantitative methods. Project benefits related to risk can then be represented by a statistical expected value calculation of avoidable social cost, comparable to existing benefit calculations based on avoidable life cycle agency cost. The likelihood models described above provide the typical probability or frequency, each year, that a service disruption event can be expected to take place. Consequence models then assign a dollar value to each disruption event.

Fortunately, the social cost calculations used in this analysis are already standardized in the AASHTO Red Book, which is widely used in life cycle cost, value engineering, and regulatory analyses (*7*). The Red Book provides unit costs for accidents, travel time, and vehicle operations. The Guidelines provide worksheets and examples of research-based procedures to estimate the safety and mobility impacts, in terms of excess accidents, hours of delay, and miles of detour. These can then be converted to dollars using AASHTO Red Book parameters.

Figure 5 shows an example worksheet for mobility consequences, which entail detours while a bridge is monitored, repaired, or rebuilt, and may have smaller impacts such as truck restrictions or speed reductions. The mobility cost per disruption event is:

$$CQ_b = ADT_b \times \frac{DD_b DL_b}{24} \times \left(VOC\$ + \frac{TT\$ \times VO}{DS_b} \right) \tag{7}$$

ADT_b = forecast vehicles per day affected
DD_b = duration of the disruption, in hours
DL_b = detour length in miles
$VOC\$$ = average vehicle operating cost per mile
DS_b = detour speed in mph
$TT\$$ = travel time cost per hour
VO = average vehicle occupancy rate, people per vehicle

This formula can be recognized as a method long used in pavement and bridge management systems for functional deficiencies, and relies on the same planning parameters. In fact, agencies using the AASHTOWare Bridge Management software may want to combine the mobility risk model and the benefit model for functional improvements, since the two models are very similar.

In addition to recovery cost, safety, and mobility, the Guideline also presents an environmental sustainability model based on estimates of vehicular emissions. It uses the approach from FHWA's Highway Economic Requirements System (*8*). This methodology, updated from earlier research in California, 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. To establish a dollar value and relative weights of the pollutants, the study uses earlier research on the economic impact on health and property damage caused by these pollutants.

Integration with Bridge Management Systems

In addition to a detailed treatment of AASHTOWare Bridge Management, the Guideline also summarizes alternative approaches to bridge management functions that incorporate risk assessment, highlighting software used in Florida, Minnesota, and New York. It also discusses the mathematical relationship with life cycle cost analysis, for agencies or vendors that may want

to develop new spreadsheets or systems that apply the models to support management functions such as treatment selection, priority setting, resource allocation, programming, and target setting.

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**

FIGURE 5 Consequence submodel for mobility

CONCLUSIONS AND FURTHER RESEARCH

The Guidelines document produced by NCHRP 20-07(378) will be of considerable help to agencies wishing to incorporate realistic risk assessment models into the decision support functions of bridge management systems. Based on a wide range of existing research studies, the models have been simplified as needed so they are compatible with the data and software commonly available to transportation agencies. When bridge management systems such as AASHTOWare Bridge Management are configured to use these models, no significant additional effort is required in order to consider risk routinely in combination with life cycle cost in decision making.

While the models are quite simple when decomposed into their parts as described here, they have the advantage that they work with data that are widely available for all bridges in an inventory, are consistent across the inventory, are sensitive to common classes of risk mitigation and replacement actions, can aggregate to reasonable estimates of systemwide risk, respond in reasonable ways to reasonable variations in the input data, and can be weighted according to

agency preferences in a transparent way. Because the models are designed to follow real-world engineering and economic relationships, they can be improved through further research when agencies desire more precision. Some examples of potential research topics are:

More and better applications

- An automated tool or spreadsheet, to implement the methods presented in the Guideline.
- Adaptation to bridge design applications to compare alternatives.
- Improved guidance on the identification and costing of risk mitigation treatments.
- Models of the effectiveness of risk mitigation actions in reducing disruption likelihood.

New or improved submodels

- Modeling of agency incident response processes and recovery costs.
- National-scale risk allocation models similar to the scour example (6).
- Incorporating carbon dioxide into the environmental sustainability model.
- Modeling sea level rise as a part of the applicable likelihood models.
- Improved modeling of flood likelihood in addition to, or combined with, scour modeling.
- A research-based model of the likelihood of over-height truck collisions.
- Further development of the likelihood model of advanced deterioration.
- Effects of bridge characteristics on vessel collision likelihood.

Implementation

- Documentation of case studies based on actual agency use.
- Training and outreach on implementation of the Guideline.

REFERENCES

1. Patidar, Vandana, Samuel Labi, Kumares Sinha, and Paul Thompson. *Multi-Objective Optimization for Bridge Management Systems*. National Cooperative Highway Research Program Report 590, Transportation Research Board of the National Academies, Washington, DC, 2007.
2. Shepard, Richard W., and Michael Johnson. "California Bridge Health Index: A Diagnostic Tool to Maximize Bridge Longevity, Investment". *TR News* 215, 2001.
3. NYSDOT. *Bridge Safety Assurance Manuals: Hydraulic, Steel Details, Overload, Collision, Concrete Details, and Seismic*. New York State Department of Transportation, Albany, NY, 2013.
4. Sobanjo, John O., and Paul D. Thompson. *Development of Risk Models for Florida's Bridge Management System: Final Report*. Florida Department of Transportation Contract BDK83 977-11, Tallahassee, FL, 2013.
5. 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*, Stresa, Italy, 2012.
6. Stein, Stuart, and Karsten Sedmera. *Risk-Based Management Guidelines for Scour at Bridges with Unknown Foundations*. National Cooperative Highway Research Program Web-Only

Document 107. Transportation Research Board of the National Academies, Washington, DC, 2006.

7. AASHTO. *User and Non-User Benefit Analysis for Highways*. American Association of State Highway and Transportation Officials, Washington, DC, 2010.
8. FHWA. *Highway Economic Requirements System – State Version: Technical Report*. Federal Highway Administration, Washington, DC, 2005.