



U.S. Department of Transportation
Federal Highway Administration

TechBrief

Framework and Methodology for Risk-Based Bridge and Tunnel Asset Management: Objective Risk Assessment and Network Level Evaluation

FHWA Publication No.: FHWA-HIF-25-012

This document is a technical summary of the report, *Framework and Methodology for Risk-Based Bridge and Tunnel Asset Management: Objective Risk Assessment and Network Level Evaluation*, available at <https://rosap.ntl.bts.gov/view/dot/79026> [1].

Introduction

Management of critical transportation assets such as bridges and tunnels has traditionally focused on condition preservation through carefully planned life-cycle activities within a budgetary limit. Although there are calls to consider various risks from extreme events, existing approaches to risk assessment in transportation asset management rely heavily on engineering judgement and past experience. This subjective and empirical approach to risk assessment contrasts to more objective methods that are underpinned by quantitative models of hazards, vulnerabilities, and consequences. Nonetheless, these quantitative models do not fully consider the effects of deterioration on structural vulnerability under extreme events, thus hindering their direct application in transportation asset management. The primary goal of this research is to facilitate risk-based transportation asset management using (a) objective and consistent risk assessment and (b) performance risk analysis for large-scale transportation networks. Three major tasks were conducted: (a) establish the general framework for objective risk assessment of deteriorating assets; (b) achieve objective agency risk assessment in transportation asset management systems; (c) develop effective and efficient methods for network-level performance risk assessment.

Notice — This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the use of the information contained in this document.

Non-Binding Contents — Except for the statutes and regulations cited, the contents of this document do not have the force and effect of law and are not meant to bind the States or the public in any way. This document is intended only to provide information regarding existing requirements under the law or agency policies.

Quality Assurance Statement — The Federal Highway Administration (FHWA) provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. FHWA periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Disclaimer for Product Names and Manufacturers — The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this document only because they are considered essential to the objective of the document. They are included for informational purposes only and are not intended to reflect a preference, approval, or endorsement of any one product or entity.

FHWA Contact — Jia-Dzwan (Jerry) Shen, Office of Bridges and Structures, (202) 336-4619, jia-dzwan.shen@dot.gov.

Researchers — This work was conducted by Portland State University under the direction of Dr. David Y. Yang, Dr. Arash Khosravifar, Dr. Diane Moug, and Dr. Avinash Unnikrishnan. The work was performed under contract 693JJ321C000030.

Key Words — Objective asset risk assessment, Performance risk of transportation networks, Performance-based asset management.

Scope

The study had the following objectives:

- Propose a practical framework for risk assessment and decision support that can be implemented with existing transportation asset management systems with minimal effort.
- Develop a practical method to objectively identify hazard scenarios used for asset risk assessment, focusing on agency risks.
- Establish a scalable approach to performance risk assessment for large-scale transportation networks.
- Identify opportunities and challenges to achieve risk-based transportation asset management using the proposed framework and methodology.

Methodology

Framework for Risk Assessment and Asset Management

Risk of transportation assets is measured by the product of the likelihood of an adverse event, the structural vulnerability to sustain damage under the event, and the anticipated outcomes given the sustained damage [2]. Among various types of extreme events, seismic events have the most established framework, known as probabilistic seismic risk assessment (PSRA) [3]. The PSRA framework not only considers all three aspects of risk, but it also accounts for the uncertainties involved in the assessment of likelihood, vulnerability, and consequence. In particular, the risk, R , is expressed by the following integral:

$$R = \int_{im} \left[\sum_{ds} cq(ds) \cdot p_{DS|IM}(ds|im) \right] \lambda_{IM}(im) dim$$

Equation 1. Risk integral.

where $cq(ds)$ = average consequence given the damage state (DS); ds [4]; $p_{DS|IM}(im)$ = probabilities of different DSs given a specific value of intensity measure (IM), obtained from a fragility model [5]; $\lambda_{IM}(im)$ = annual likelihood for a specific value of IM, as indicated by a hazard model [6]. With this framework, the risk is derived from physics-based quantitative models, thereby enabling objective risk assessment with a minimum amount of subjectivity.

Although this framework has been applied in several tools for risk and resilience assessment [7,8], these existing tools do not fully consider the deteriorated conditions of transportation assets, even if deterioration may affect structural vulnerability under extreme events [9].

To unify risk assessments described above with the transportation asset management (TAM) practice, we first introduced the risk of deterioration-induced service disruption, R_{det} , described by the following equation:

$$R_{det} = \sum_{cr} cq_f \cdot p_f(cr) \cdot p_{CR}(cr)$$

Equation 2. Deterioration risk.

where cq_f = disruption consequence; CR = condition rating (CR) used as the IM of deterioration; $p_f(cr)$ = annual failure rate given a CR, used to model structural vulnerability to deterioration.

To reflect deterioration on extreme event risks, the expected consequences given an IM value, i.e., the term in the square brackets in Equation 1, was revised as follows:

$$\overline{CQ}(im|t) = \sum_{ds} cq(ds) \cdot p_{DS|IM}(ds|im, t)$$

Equation 3. Time-based expected consequence.

$$\overline{CQ}(im|cr) = \sum_{cr} \sum_{ds} p_{CR}(cr) \cdot cq(ds) \cdot p_{DS|IM}(ds|im, cr)$$

Equation 4. CR-based expected consequence.

where $\overline{CQ}(im|t)$ = expected consequence given $IM=im$ when a time-based fragility model, i.e., $p_{DS|IM}(ds|im, t)$, is used to reflect the deterioration effect; $\overline{CQ}(im|cr)$ = expected consequence using a CR-based fragility model, i.e., $p_{DS|IM}(ds|im, cr)$; $p_{CR}(cr)$ = probability of $CR = cr$.

Based on the formulation from Equation 1 to Equation 5, the unified framework was established by considering TAM as a problem of minimizing the total risk due to deterioration and extreme events. Data needs for this framework, as well as existing sources and knowledge gaps, are further clarified and summarized in the full report [1].

Objective Hazard Selection for Agency Risk Assessment

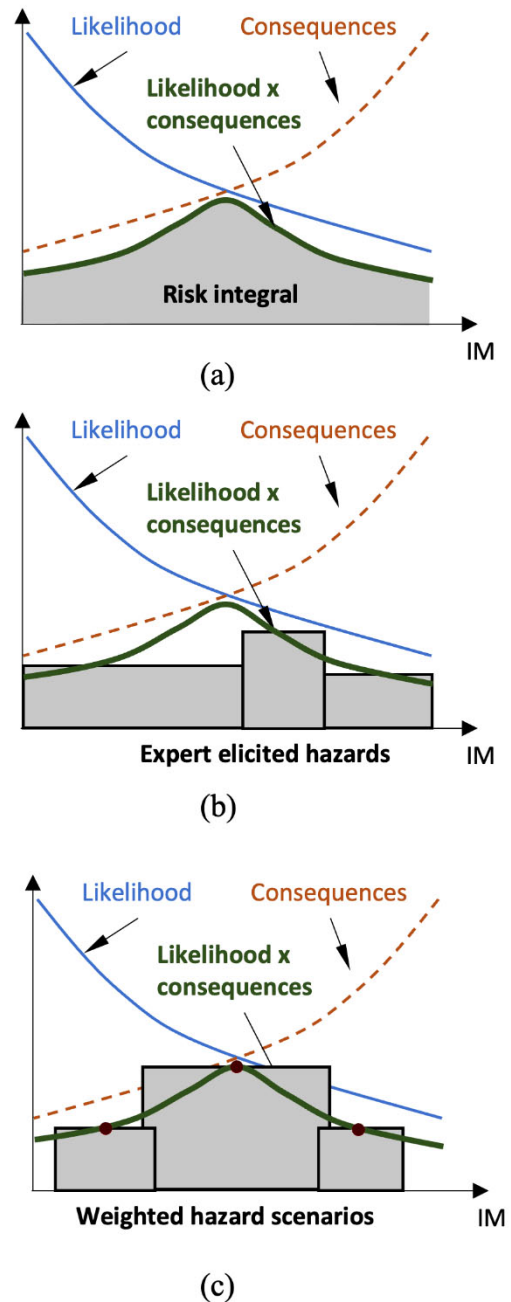
Although the risk integral provides a consistent and objective framework for risk assessment, it differs considerably from the risk assessment practice in TAM. The risk integral accounts for all potential IM values based on the hazard model, while the existing TAM practice uses a small set of hazard scenarios subjectively identified by an expert panel [3]. This subjective approach in practice may result in inconsistent assessment results among different panels or for different hazards, and add much burden to asset managers in making important decisions on selecting critical scenarios in risk tables.

To reduce the effort required to calculate the risk integral, an approach was proposed to (a) select hazard scenarios that can efficiently and objectively estimate the risk integral and (b) preserve the general format of a risk table for seamless integration with bridge management practices. This approach, named the weighted hazard scenario approach to risk assessment, was built on the Gaussian quadrature method for the numerical integration of the risk integral.

Figure 1 conceptually illustrates the Gaussian quadrature method. The analytical expression of the risk integral is illustrated in Figure 1(a), where the shaded area under the multiplication of the hazard likelihoods and consequences represents the precise value of the risk integral. Figure 1(b) exemplifies the identified hazard IMs and consequences in the traditional process of expert elicitation. Based on Gaussian quadrature, the weighted hazard scenario approach can strategically select the hazard scenarios, represented by the locations of the highlighted points in Figure 1(c), and the weights of the selected scenarios, represented by the widths of the rectangles in Figure 1(c). Consequently, with the same number of hazard scenarios, the risk integral can be more accurately estimated.

The complete formulation of the proposed approach can be found in the full report [1]. To facilitate the application of the weighted hazard scenario approach, a program named pyRiskTable was developed. The program can automatically generate a risk table as a comma-separated values (CSV) file based on custom-

defined hazard, structural fragility, and damage consequence models. Each scenario includes its IM value, responsibility weight to the total risk, a nominal annual rate of occurrence, and the expected consequence given the occurrence of the scenario.



Source: FHWA

Figure 1. Concept of Gaussian quadrature for numerical integration: (a) precise risk integral, (b) risk estimated by expert elicitation, and (c) weighted hazard scenarios from Gaussian quadrature.

Performance Risk Assessment of Large-Scale Transportation Networks

Apart from direct financial risks to the owner agencies, highway systems also carry important functions for freight and personal transport. These indirect consequences of asset failure may demonstrate the so-called “network effect”, under which the combined impact of risk on multiple assets is different from the total impact of risk on each asset. This network effect arises primarily due to the interdependency of assets in an interconnected network such as transportation systems [10].

Examples of transportation performance that may exhibit network effects include accessibility to critical services, freight capacity, and travel time of road users [11]. The performance risk, ρ_{NET} , of a transportation network can be expressed as [12]:

$$\rho_{NET} = \sum_s p(\mathbf{s}) \cdot |C_{NET}(\mathbf{s}) - C_{NET,0}|$$

Equation 5. Performance risk of networks.

where $p(\mathbf{s})$ = probability of the system state \mathbf{s} , which includes conditions of all assets in the system; $C_{NET}(\mathbf{s})$ = system-level performance given the system state \mathbf{s} ; $C_{NET,0}$ = system-level performance without any damage.

The evaluation of system-level performance calls for the complete knowledge of all asset conditions. For a large-scale transportation network with hundreds to thousands of assets, assessing the performance risk is complicated by the enormous amount of unique system states. As a result, existing approaches either deal only with small networks with dozens of assets [13,14] or rely on Monte Carlo (MC) simulation [15,16], which, although scalable, may give unreliable risk estimates when or if the performance risk is heavily influenced by systems states with low likelihood of occurrence but high consequences, i.e., the so-called “grey swan” events.

To overcome the shortcomings of existing methods, a novel sampling method was developed. Specifically, the risk calculated in Equation 5 was reformulated to the evidence term in Bayesian updating. A Transitional Markov chain Monte Carlo (TMCMC) algorithm [17] was then leveraged to approximate the risk in a sequential process, during which the sampling effort shifts from the prior joint distribution

of asset conditions to the system states more critical to estimating the performance risk. More details on the weighted hazard scenario approach can be found in the full report [1].

Results & Discussion

Seismic Risk Assessment with the Weighted Hazard Scenarios

Comparison with the BMS practice

The weighted hazard scenario approach, as outlined previously and detailed in the full report [1], was compared with the expert-elicited approach from NCHRP Project 20-07/Task 378 [3] and adopted in several bridge management systems (BMSs).

The example bridge, its fragility model, and the damage consequences can be found in the full report [1]. The seismic risk was selected as the example due to the availability of data and models associated with earthquake hazards compared to other extreme events. The hazard IM and the annual rate of exceedance were characterized by the hazard curve in Baker (2013) [6]. The bridge fragility curves and the consequences for different DSs were selected from Basöz et al. (1999) [4].

Table 1 and Table 2 present the risk tables obtained from the expert-elicited approach and the weighted hazard scenario approach, respectively. Table 1 shows the hazard scenarios with return periods commonly used in expert-based seismic risk assessment or seismic design of structures. All scenarios contributed equally to the total seismic risk of the bridge. With the weighted hazard scenario approach, the hazard scenarios as well as their responsibility weights in Table 2 were derived from the Gaussian points used to carry out the risk integral. Since using more scenarios typically results in better accuracy, both approaches were compared using the same number of scenarios for the risk analysis for an equal comparison. Using the weighted hazard scenario approach, additional scenarios beyond six did not significantly improve prediction accuracy.

The benchmark seismic risk for the bridge was calculated as 0.00332 based on Equation 1 using a numerical integration tool. This risk value is relatively low because (a) the value corresponds to an annual risk and (b) the assumed fault only generates

magnitude 6.5 earthquakes with a return period of 100 years [6].

Table 1. Risk assessment based on the expert-elicited approach.

Source: FHWA

Hazard scenario	Description (return period, PGA in g)	Annual rate	Consequence (cost ratio)	Risk (cost ratio)
1	225 yr, PGA=0.326	2.444E-03	0.326	7.958E-04
2	500 yr, PGA=0.554	9.740E-04	0.554	5.397E-04
3	975 yr, PGA=0.691	3.590E-04	0.691	2.480E-04
4	1500 yr, PGA=0.758	1.670E-04	0.758	1.266E-04
5	2000 yr, PGA=0.795	9.600E-05	0.795	7.633E-05
6	2475 yr, PGA=0.819	4.040E-04	0.819	3.309E-04
Total risk				0.002117

Table 2. Risk assessment based on the proposed approach using weighted hazard scenarios.

Source: FHWA

Hazard scenario	Description (return period, PGA in g)	Annual rate	Consequence (cost ratio)	Weight	Risk (cost ratio)
1	104 yr, PGA=0.136	1.119E-02	0.021	0.171	4.078E-05
2	240 yr, PGA=0.424	1.712E-02	0.348	0.361	2.148E-03
3	1435 yr, PGA=0.873	2.855E-03	0.752	0.468	1.004E-03
4	8873 yr, PGA=1.379	3.991E-04	0.916	0.468	1.711E-04
5	36247 yr, PGA=1.828	8.597E-05	0.966	0.361	2.995E-05
6	82265 yr, PGA=2.116	3.502E-05	0.980	0.171	5.879E-06
Total risk					0.00340

Based on this benchmark, the weighted hazard scenario approach resulted in a negligible error in the estimated risk (0.00340 vs. 0.00332). The expert-elicited approach underestimated the precise value by 36% (0.002117 vs. 0.00332).

Potential effect on asset management

The risk value obtained above is only a snapshot (i.e., annual risk of a pristine bridge) of the entire risk profile within its service life. With deterioration, the seismic fragility curves change over time. It is important to verify whether the hazard scenarios in Table 2 as well as their corresponding weights can also accurately estimate the risk for deteriorated assets. To this end, the research team assumed an exaggerated deterioration rate over a service life of 75 years. This deterioration was represented by reducing the median IM of the fragility curves. Detailed description and justification for the assumed deterioration can be found in the full report [1].

Figure 2 shows the risk profile in the 75-year service life using the scenarios and weights in Table 2. The effect of deterioration was accounted for by using age-based fragility curves, which increased the

expected consequences associated with each hazard scenario. The risk profile was compared with the precise risk profile, also shown in Figure 2, obtained by evaluating the risk integral in each year of the service life with a numerical integration tool. The difference between the two profiles represents the error in risk assessment when using the same set of weighted hazard scenarios derived for a pristine bridge. Figure 2 indicates that this error is negligible in the entire service life for the assumed extent of deterioration. Since the assumed deterioration is conservative (i.e., overestimating the capacity loss), the error in more realistic settings can also be negligible.

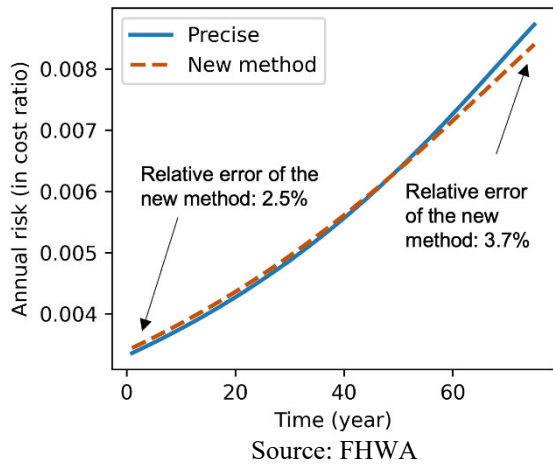


Figure 2. Error of using the same set of hazard scenarios and scenario weights for deteriorating assets.

Due to the improved accuracy in the estimated risk, the weighted hazard scenario approach can better quantify the risk reduction associated with maintenance and retrofitting activities in the service life. The project compared two hypothetical maintenance sequences (i.e., life-cycle plans) to demonstrate the implications of accurate risk assessment on asset management. Each asset was assumed to be restored to its pristine condition by each maintenance action. The cost of the restoration was assumed to be proportional to the capacity improvement needed. Detailed descriptions of the decision-making problem and other relevant assumptions can be found in the full report [1]. Figure 3 presents the benefit-to-cost ratios of both plans, evaluated based on both the weighted hazard scenario and the conventional BMS approaches. The comparison indicates that the conventional approach may not deliver reliable rankings for different life-cycle plans.

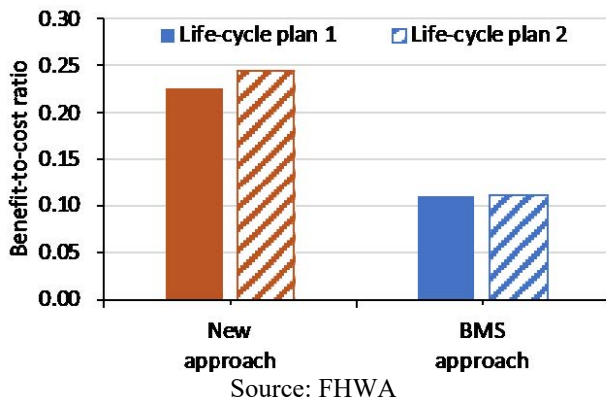


Figure 3. Benefit of objective risk assessment: more reliable comparison between life-cycle plans.

Validation and Application of the TMCMC Algorithm for Performance Risk Assessment

Algorithm verification via analytical examples

The effectiveness and efficiency of the developed TMCMC algorithm were first investigated based on a series of analytical examples. The investigation focused on the influence of “grey swan” events, which may occur due to network effects. The analytical examples were designed such that (a) the number of assets was large enough to invalidate existing non-simulation-based methods that can handle “grey swan” events, and (b) the precise risk was still tractable despite the large number of assets. The full report [1] includes the detailed setup of the analytical examples.

Figure 4 presents the results of the estimated risks using (a) crude Monte Carlo (MC) simulation and (b) the proposed TMCMC algorithm. The comparison was based on the same number of performance evaluations, i.e., computation of $\rho_{NET}(\mathbf{s})$ in Equation 5 for different samples of \mathbf{s} . To draw statistically significant conclusions, the risk assessment was conducted 10 times using each method with different random seeds. Figure 4 indicates that the proposed TMCMC method can accurately estimate the performance risk even when “grey swan” events are involved. The observed error ranged from -11.31% to $+7.18\%$ compared to the precise risk, with the mean of the 10 implementations closely matching the precise value (44.659 vs 45.001). In contrast, the MC method failed to reliably estimate the risk due to the difficulty in sampling “grey swan” events. Most of the 10 MC implementations yielded severely underestimated risk due to the lack of representation of “grey swan” events among the samples. Occasionally, the “grey swan” events were overrepresented, yielding drastically overestimated risk values.

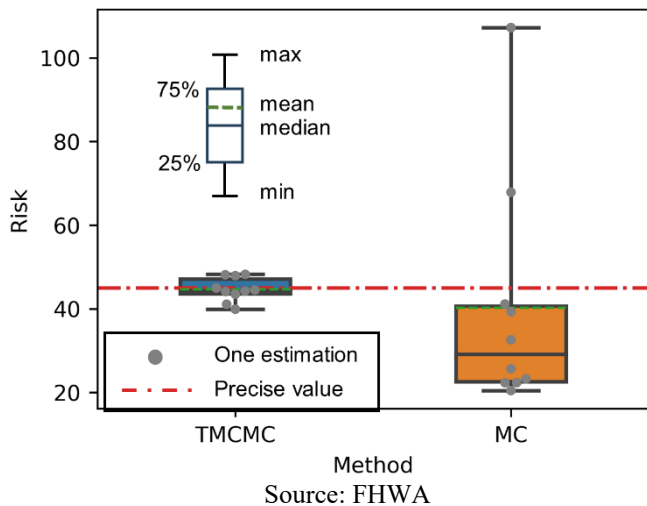


Figure 4. Method comparison using analytical examples involving network effects and grey swan events.

Case study with Oregon highway network

To demonstrate the scalability of the proposed TMCMC method, a transportation network of a realistic scale was analyzed for its performance risk in terms of freight capacity losses due to potential bridge failures. The case study focused on the entire Oregon highway network with thousands of vulnerable bridges. The reliability index of each link with vulnerable bridges was randomly assigned. Due to this random assignment of link reliability, the results of this case study should be viewed only for algorithmic validation purposes and should not be regarded as the actual risk related to the Oregon highway network. The goal of the case study was to test the effectiveness of the TMCMC method for realistic large-scale networks.

The network model was developed based on several publicly available or open-source mapping and geospatial databases. The resulting model is a graph comprising 6,437 nodes and 10,637 links, among which 1,938 are vulnerable bridge links (i.e., assets). The freight capacity of the intact or damage network was computed using a preflow-push algorithm used for analyzing complex networks. More details regarding the data collection and preprocessing can be found in the full report [1].

Using the TMCMC method, the performance risk of this network was estimated at 0.3360. This indicates that given the failure probabilities of the 1,938 bridge links, the expected decrease in freight capacity is 33.60%. The computation was carried out on a stack server using 80 processes and had a wall-clock

runtime of 22.66 hours. In total, 44,213 unique system states were analyzed. The result demonstrates the effectiveness of the TMCMC method in a large-scale network.

In addition to assessing risk, the TMCMC method can identify routes and assets that contribute the most to the performance risk, thereby offering insights to intervention prioritization. Based on the case study results, Figure 5 presents the identified routes that significantly impact the performance risk. Note that the results herein hinge on several assumptions, e.g., the failure probabilities of different bridges. Therefore, it is reiterated that the results should not be considered the actual vulnerable assets within the Oregon highway network.

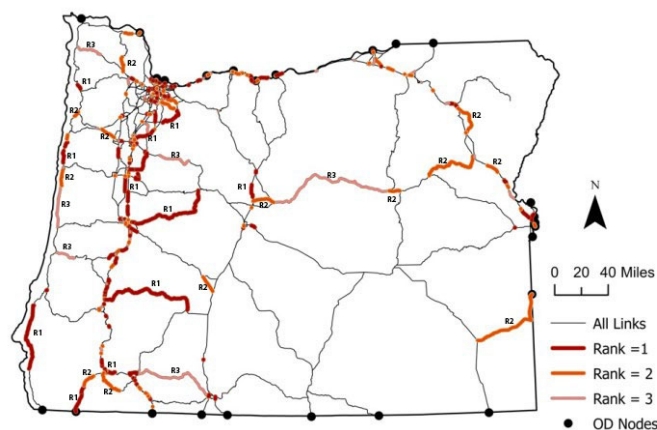


Figure 5. High-risk routes in Oregon highway network identified with the TMCMC method.

Conclusions

Practical frameworks and methods for risk-based bridge and tunnel management were developed in this project. Both direct and indirect risk analyses were considered. The following conclusions can be drawn from this project:

- Risks from structural deterioration and extreme events can be integrated to obtain lifetime risks expressed in monetary units. This integration allows for risk-based bridge and tunnel management to better coordinate between condition preservation and risk mitigation activities. To realize these benefits, it is important to provide objective risk estimates that are consistent across different hazards, analysis tools, and transportation agencies.

- To achieve consistent and objective risk assessment, a novel approach using weighted hazard scenarios was established to fill the gap between risk analysis and asset management. Rather than rely on expert elicitation to identify hazard scenarios, the weighted hazard scenario approach can generate scenarios that best capture risks from various hazard intensities and frequencies, structural fragilities, and damage consequences. This enables simple and accurate risk assessment that can be consistently applied to different hazards and limits biases from the agency or its analysts. The weighted hazard scenario approach maintains the simplicity of the expert-elicited approach currently used in BMS, but can yield much higher accuracy compared with the benchmark produced by comprehensive risk integral.
- The weighted hazard scenario approach to objective risk assessment was also applied to interacting hazards such as the seismic events compounded by structural deterioration. For stationary hazards (i.e., hazard frequency and intensity do not change over time), it was found that as long as the deterioration effect is reflected in the expected consequences for different hazard scenarios, the same set of hazard scenarios can be used over the entire service life of a structure without introducing noticeable errors. It was also demonstrated that inaccurate risk assessment may obscure the benefit-to-cost ratios of different maintenance strategies.
- An effective and efficient method was developed to assess the indirect risk of large-scale transportation asset networks. The advantage of the TMCMC method is especially salient when (a) the performance indicator exhibits network effects, i.e., when the system-level failure consequences is more severe than the sum of consequences of individual failures, and (b) when the performance risk is dominated by low probability, high consequence events. The TMCMC method was shown to be able to handle regional transportation networks of realistic scales (e.g., hundreds to thousands of assets). In addition to assessing risk, the method can also identify routes and assets that contribute the most to the performance risk, thereby offering insights to intervention planning.

References

- [1] D.Y. Yang, A. Khosravifar, D. Moug, A. Unnikrishnan, Framework and Methodology for Risk-Based Bridge and Tunnel Asset Management: Objective Risk Assessment and Network Level Evaluation, Portland State University, Portland, OR, 2024. <https://rosap.nhl.bts.gov/view/dot/79026>.
- [2] ASME, All-Hazards Risk and Resilience: Prioritizing Critical Infrastructures Using the RAMCAP Plus Approach, American Society of Mechanical Engineers (ASME), New York, NY, 2009.
- [3] J. Western, P. Bye, M. Valeo, P.D. Thompson, E. Frazier, NCHRP 20-07/Task 378 Final Report: Assessing Risk for Bridge Management, National Cooperative Highway Research Program (NCHRP), Washington, DC, 2016.
- [4] N. Basöz, J.B. Mander, Enhancement of the Highway Transportation Lifeline Module in HAZUS, National Institute of Building Sciences, 1999.
- [5] A.H.M. Muntasir Billah, M. Shahria Alam, Seismic fragility assessment of highway bridges: a state-of-the-art review, Structure and Infrastructure Engineering 11 (2015) 804–832. <https://doi.org/10.1080/15732479.2014.912243>.
- [6] J.W. Baker, Introduction to Probabilistic Seismic Hazard Analysis, White Paper Version 2.0.1 (2013). <http://dx.doi.org/10.1016/j.strusafe.2008.06.002>.

- [7] FEMA, HAZUS Earthquake Model Technical Manual (HAZUS v4.2 SP3), Federal Emergency Management Agency (FEMA), Washington, DC, 2020.
- [8] NIST, Interdependent Networked Community Resilience Modeling Environment (IN-CORE), (2023). <https://incore.ncsa.illinois.edu> (accessed November 2, 2023).
- [9] A. Bhandari, Uncertainty Quantification and Fragility Development of Deteriorating RC Bridge Piers, Portland State University, 2023. <https://doi.org/10.15760/etd.8168>.
- [10] D.Y. Yang, D.M. Frangopol, Risk-informed bridge ranking at project and network levels, *Journal of Infrastructure Systems* 24 (2018) 04018018. [https://doi.org/10.1061/\(ASCE\)IS.1943-555X.0000430](https://doi.org/10.1061/(ASCE)IS.1943-555X.0000430).
- [11] L. Chang, F. Peng, Y. Ouyang, A.S. Elnashai, B.F. Spencer, Bridge seismic retrofit program planning to maximize postearthquake transportation network capacity, *Journal of Infrastructure Systems*, ASCE 18 (2012) 75–88. [https://doi.org/10.1061/\(ASCE\)IS.1943-555X.0000082](https://doi.org/10.1061/(ASCE)IS.1943-555X.0000082).
- [12] D.Y. Yang, Deep Reinforcement Learning–Enabled Bridge Management Considering Asset and Network Risks, *Journal of Infrastructure Systems* 28 (2022) 04022023. [https://doi.org/10.1061/\(ASCE\)IS.1943-555X.0000704](https://doi.org/10.1061/(ASCE)IS.1943-555X.0000704).
- [13] D. Saydam, P. Bocchini, D.M. Frangopol, Time-dependent risk associated with deterioration of highway bridge networks, *Engineering Structures* 54 (2013) 221–233. <https://doi.org/10.1016/j.engstruct.2013.04.009>.
- [14] M. Bensi, A.D. Kiureghian, D. Straub, Framework for post-earthquake risk assessment and decision making for infrastructure systems, *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* 1 (2015) 04014003. <https://doi.org/10.1061/AJRUA6.0000810>.
- [15] K. Rokneddin, J. Ghosh, L. Dueñas-Osorio, J.E. Padgett, Seismic reliability assessment of aging highway bridge networks with field instrumentation data and correlated failures, II: Application, *Earthquake Spectra* 30 (2014) 819–843. <https://doi.org/10.1193/040612EQS160M>.
- [16] N. Vishnu, S. Kameshwar, J.E. Padgett, Road transportation network hazard sustainability and resilience: correlations and comparisons, *Structure and Infrastructure Engineering* 19 (2023) 345–365. <https://doi.org/10.1080/15732479.2021.1945114>.
- [17] J. Ching, Y.-C. Chen, Transitional Markov Chain Monte Carlo Method for Bayesian Model Updating, Model Class Selection, and Model Averaging, *Journal of Engineering Mechanics* 133 (2007) 816–832. [https://doi.org/10.1061/\(ASCE\)0733-9399\(2007\)133:7\(816\)](https://doi.org/10.1061/(ASCE)0733-9399(2007)133:7(816)).