# SUMMARY OF NCHRP RESEARCH ON DEVELOPMENT OF RISK-BASED BRIDGE INSPECTION PRACTICES

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## Abstract

This paper summarizes the findings of two NCHRP projects conducted to (1) develop guideline for reliability-based bridge inspection practices based on rational methods to improve the safety and reliability of bridges by focusing inspection efforts where most needed and optimizing the use of resources; and (2) conduct case studies of the application of the proposed Guideline. The Guideline describes a methodology to develop a risk-based approach for determining the bridge inspection interval according to the requirements in the “Moving Ahead for Progress in the 21st Century Act (MAP-21)” legislation.

## Introduction

The National Bridge Inspection Standards (NBIS) mandate the frequency and methods used for the safety inspection of highway bridges. The inspection intervals specified in the NBIS require routine inspections to be conducted every 24 months, and that interval may be extended to 4 years for bridges that meet certain criteria and are approved by the Federal Highway Administration (FHWA). For bridges with fracture-critical elements, hands-on inspections are required every 2 years. The specified intervals are generally not based on performance of bridge materials or designs, but rather on experience from managing almost 600,000 bridges in the National Bridge Inventory (NBI).

These inspection intervals are applied to the entire bridge inventory, but they may not be appropriate for all bridges. For example, recently constructed bridges typically experience few problems during their first decade of service and those problems are typically minor. Under the present requirements, these bridges must have the same inspection frequency and intensity as a 50-year-old bridge that is reaching the end of its service life. In the case of bridges with fracture-critical elements, newer bridges with improved fabrication processes and designs that mitigate the effects of fatigue are inspected on the same interval and to the same intensity as older bridges that do not share these characteristics.

A more rational approach to determining appropriate inspection practices for bridges would consider the structure type, age, condition, importance, environment, loading, prior problems, and other characteristics of the bridge. There is a growing consensus that these inspection practices should meet two goals: (1) improving the safety and reliability of bridges and (2) optimizing resources for bridge inspection. These goals can be accomplished through the application of reliability theory.

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This paper summarizes the research conducted under two NCHRP projects to achieve the research objectives. This summary is extracted from the *NCHRP Report 782: Proposed Guideline for Reliability-Based Bridge Inspection Practices* authored by the principal investigator Dr. Glenn Washer, associate professor at the University of Missouri and the co-principal investigator Dr. Robert Connor, associate professor at Purdue University (Washer et al. 2014).

## Methodology

The risk-based inspection (RBI) process involves an owner (e.g., state) establishing a reliability assessment panel (RAP) to define and assess the durability and reliability characteristics of bridges within their state. The RAP uses engineering rationale, experience and typical deterioration patterns to evaluate the reliability characteristics of bridges and the potential outcomes of damage. This is done through a relatively simple process that consists of three primary steps:

**Step 1: What can go wrong, and how likely is it?** Identify possible damage modes for the elements of a selected bridge type. Considering design, loading and condition characteristics (attributes), categorize the likelihood of serious damage occurring into one of four Occurrence Factors (OFs) ranging from remote (very unlikely) to high (very likely).

**Step 2: What are the consequences?** Assess the consequences, in terms of safety and serviceability, assuming the given damage modes occur. Categorize the potential consequences into one of four Consequence Factors (CFs) ranging from low (minor effect on serviceability) to severe (e.g., bridge collapse, loss of life).

**Step 3: Determine the inspection interval and scope.** Use a simple reliability matrix to prioritize inspection needs and assign an inspection interval for the bridge based on the results of Steps 1 and 2. Damage modes that are likely to occur and have high consequences are prioritized over damage modes that are unlikely to occur or are of little consequence in terms of safety. An RBI procedure is developed based on typical damage modes that occur when the maximum inspection interval is specified.

Inspections are conducted according to the RBI procedure developed through this process. The RBI procedure differs from current inspection practices because the typical damage modes for a specific bridge are identified and prioritized, and the inspection must assess each of these damage modes sufficiently to identify the needs for further assessment. As a result, the inspections may be more thorough than traditional practices, including hands-on access to key portions of a bridge such that damage is effectively identified. The results of the inspection are assessed to determine if the existing RBI procedure needs to be modified or updated. For example, as a bridge deteriorates over time and damage develops, as reported in the inspection results, inspection intervals may be reduced to address the need for frequent assessment as the bridge ages.

The assessment process includes the developed Guideline is shown schematically in Figure 1. The process begins with the selection of a bridge or family of similar bridges to be analyzed. For the selected bridge or bridges, the RAP identifies common damage modes for elements of the bridge considering the design, materials, and operational environment. Key attributes are identified and ranked to assess OFs that categorize the likelihood of serious damage developing over a specified time interval. CFs that categorize the potential outcomes or consequences of damage are also assessed. Based on the assessment of the OFs and CFs for the various elements of the bridge, an inspection procedure is established, including the interval and scope for the inspection. Criteria for reassessment of the inspection procedure are also developed based on conditions that may change as a result of deterioration or damage and affect the OFs for the bridge. The RBI practice is then implemented in the subsequent inspection of the bridge. Inspection results are assessed to determine if any established criteria have not been met, or if conditions have changed that may require a reassessment of the OFs. If such changes exist, a reassessment of the OFs is made and the inspection practice modified accordingly.

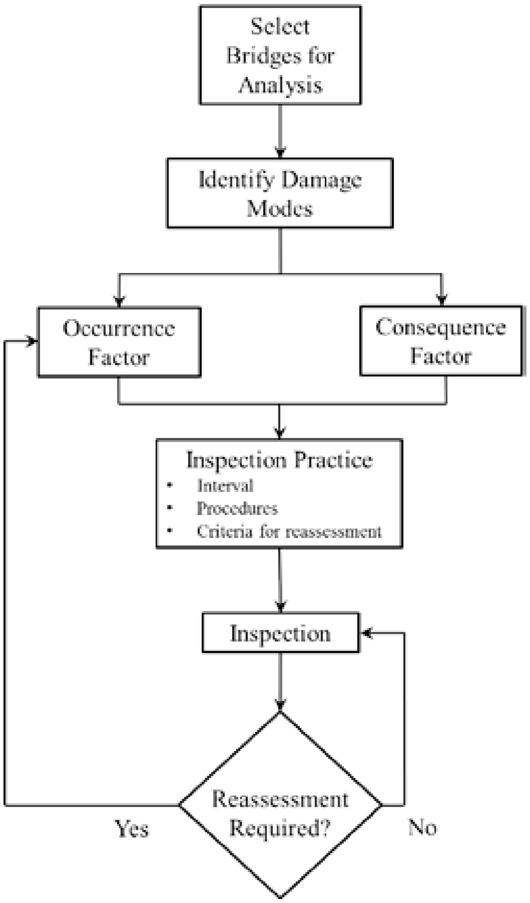


**Figure 1: Schematic Diagram of the RBI Process**

The method of determining the inspection interval, or time period between inspections, is shown schematically in Figure 2. The interval is based on the RAP assessment of the Occurrence and the CFs, plotted on a simple two-dimensional reliability matrix as shown in the Figure. The Occurrence and Consequence Factors are used to place typical damage modes in an appropriate location on the matrix. In this Figure, the horizontal axis represents the CF as determined for a particular damage mode for a given bridge element. The vertical axis represents the outcome of the OF assessment for a given damage mode for the given element. Damage modes that tend toward the upper right corner of the matrix, meaning they are likely to occur and have high consequences if they did occur, require shorter inspection intervals and possibly more intense  or focused inspections. Damage modes that tend toward the lower left corner, meaning they are unlikely occur, and/or consequences are low if they did occur, require less frequent inspection. This is simply a rational approach to focusing inspection efforts; inspections are most beneficial when damage is likely to occur and is important to the safety of the bridge; inspections are less beneficial for things that are very unlikely to occur, or are not important to the safety or serviceability of the bridge.

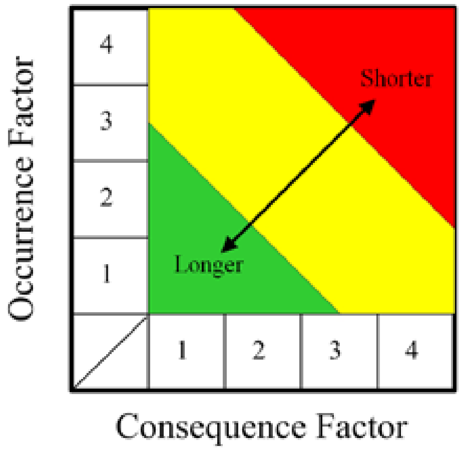


**Figure 2: Reliability Matrix for Determining Change in Inspection Intervals**

Through this process, individual bridges, or families of bridges of similar design characteristics, can be assessed to evaluate inspection needs from a reliability-based engineering assessment of the likelihood of serious damage occurring, and the effect of that damage on the safety of the bridge. The methodology can be applied throughout a bridge inventory, or to portions of a bridge inventory. Suitable Quality Control (QC) and Quality Assurance (QA) procedures should be utilized to ensure consistency.

The RBI approach considers the structure type, age, condition, and operational environment in a systematic manner to provide a rational assessment process for inspection planning. A documented rationale for the inspection strategy utilized for a given bridge is developed. The damage modes most important to ensuring the safety of the bridge are identified such that inspection efforts can be focused to improve the reliability of the inspection results.

## Damage Modes

The first step in the process is to answer the question “What can go wrong?” For most common bridges, the damage modes that affect the bridge are well known. Spalling and cracking of the concrete as a result of corrosion, or section loss and fatigue cracking in steel elements, are typical examples. The RAP, through a consensus process utilized current and past research and experience, develops a listing of the credible damage modes for the elements of a bridge or a family of bridges being assessed. A credible damage mode is one that could reasonably or typically be expected to occur during the service life of the bridge element. Table 1 lists examples of typical damage modes for several common bridge elements that may be identified by the RAP.

**Table 1: Typical Damage Modes for Common Bridge Elements**

| Element | Damage Modes |
|---|---|
| **Steel Girder** | Corrosion damage/section loss |
| | Fatigue cracking |
| | Fracture |
| | Impact damage |
| **Prestressed Girder** | Corrosion damage (spalling/cracking) |
| | Strand fracture |
| | Shear cracking |
| | Flexural cracking |
| | Impact damage |
| **Piers and Abutment** | Corrosion damage (spalling/cracking) |
| | Damage to bearing areas |
| | Unexpected settlement / rotation |

An expert elicitation process may be used to identify the typical damage modes for consideration. This process may also be used to identify unusual or uncommon damage modes that may be relevant for a particular bridge inventory. Each member of the RAP is then asked to list the damage modes that they identify as the most likely causes (e.g. cracking, section loss) for the member condition, and estimate its relative likelihood of being the cause, relative to other damage modes they identify. The results of this independent exercise are then aggregated as shown in Table 2, showing illustrative results from a six member RAP team assessing the given element scenario.

**Table 2: Expert Elicitation of Damage Modes for Steel Girders**

| Damage | Expert 1 | Expert 2 | Expert 3 | Expert 4 | Expert 5 | Expert 6 | Average |
|---|---|---|---|---|---|---|---|
| Corrosion / section loss | 60 % | 60% | 50% | 50% | 70% | 50% | 57% |
| Fatigue | 30% | 30% | 30% | 20% | 10% | 20% | 23% |
| Overload | 10% | 10% | 10% | 20% | 20% | 20% | 15% |
| Impact | 0% | 0% | 10% | 10% | 0 | 10% | 5% |
| Sum | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

## Occurrence Factors

The OFs represent a probability of failure (POF) estimate over a time period selected based on engineering factors that includs prior research, analysis of data from the NBI, expert judgment and data from corrosion and damage models. It is also selected as a time interval for which an engineer could reasonably be expected to estimate future performance within four fairly broad categories, ranging from “remote” to “high,” based on key attributes that describe the design, loading and condition of a bridge or bridge element. In addition, this time interval was selected to provide a suitable balance between shorter intervals, when the POF could be unrealistically low due to the typically slow progression of damage in bridges, or longer intervals, where uncertainty would be increasingly high.

The analysis provides the rationale for categorizing the OFs on a rating scale from “remote,” when the likelihood is extremely small such that it would be unreasonable to expect failures, to “high,” where the likelihood is increased. This rating scale is shown in Table 3. In some cases, the OF may be an estimate of the likelihood of a certain adverse event occurring that results in a failure, such as impact from an over-height vehicle or an overload.

**Table 3: Occurrence Factor Rating Scale for RBI**

| Level | Category | Description |
|---|---|---|
| 1 | Remote | Remote likelihood of occurrence, unreasonable to expect failure to occur |
| 2 | Low | Low likelihood of occurrence |
| 3 | Moderate | Moderate likelihood of occurrence |
| 4 | High | High likelihood of occurrence |

An expert elicitation process may be used to quantitatively describe occurrence factor categories. For example, if you asked an expert to estimate the probability of serious corrosion damage (widespread spalling, for example) for particular bridge deck given its current condition, a common engineering response might include a percentage estimate, for example less than 0.1% chance or less than 1 in a thousand. This estimate can then be mapped to the qualitative scale as being “low.” Such estimates are typically very conservative, particularly for lower, less likely events. For engineering estimates of the likelihood of a failure occurring for a given bridge element, the qualitative scale can be interpreted as shown in Table 4.

**Table 4: Percentage Estimates for Occurrence Factor Ratings**

| Qualitative Description | Expressed as a percentage |
|---|---|
| Remote | 0.01% or less |
| Low | 0.1% or less |
| Moderate | 1% or less |
| High | > 1% |

## Consequence Factors

Within an RBI process, the CF is used to categorize the outcome or the result of the failure of a bridge element due to a given damage mode. For example, brittle fracture is one of the key damage modes pertaining to steel bridges. Should brittle fracture of a girder occur, the next logical question becomes, “what is the consequence?” This would obviously depend on the specific scenario for the fracture. If the member was classified as fracture critical, such an event may be catastrophic, or one that would be considered to be a severe consequence. However, if the girder was one member of a multi-girder short span bridge, the consequence of that fracture would likely to be much less serious, perhaps requiring a lane closure or even temporary closure of the bridge, or a high consequence. “Multi-girder” bridges described herein are bridges with four or more main load bearing members.). In fact, in some cases, such an event may only have moderate consequences.

The CF is used to categorize the consequence of failure of a bridge element into one of four broad categories: Low, Moderate, High, and Severe. Table 5 shows the general descriptions for each of the CF categories used for the RBI assessment. The general descriptions are indicated in terms of safety and serviceability of the bridge, graduated with qualitative descriptions. Both long and short term consequences should/may be considered.

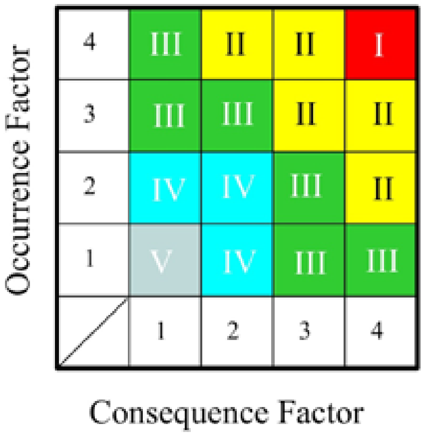
**Table 5: General Description of the Consequence Factors Categories**

| Level | Category | Consequence on Safety | Consequence on Serviceability | Summary Description |
|---|---|---|---|---|
| **1** | **Low** | None | Minor | Minor effect on serviceability, no effect on safety |
| **2** | **Moderate** | Minor | Moderate | Moderate effect on serviceability, minor effect on safety |
| **3** | **High** | Moderate | Major | Major effect on serviceability, moderate effect on safety |
| **4** | **Severe** | Major | Major | Structural collapse / loss of life |

An expert elicitation of the RAP can be a useful tool for evaluating the appropriate CF. Independently, each member of the RAP is asked, based on their judgment, experience, available data, and given the scenario presented, to determine what the most realistic consequence is resulting from the damage mode under consideration. The expert is asked to express this as a percentage, with the smallest unit of estimate typically being 10%. The expert provides a written statement on what factors they considered in making the estimate.

## Inspection Interval

Inspection intervals are determined based on the reliability analysis using a simple four by four matrix as shown in Figure 3, which illustrates a risk matrix for a typical highway bridge.  Engineering judgment is required for establishing the specific divisions applied to the risk matrix; the divisions are generally applied to ensure that the likelihood of damage remains low during the interval between inspections, such that there are multiple inspections conducted before there is a high likelihood of failure occurring. When consequences are relatively high, should the failure occur, the interval is further reduced to provide an extra margin of safety.



| | | | | |
|---|---|---|---|---|
| 4 | III | II | II | I |
| 3 | III | III | II | II |
| 2 | IV | IV | III | II |
| 1 | V | IV | III | III |
| | 1 | 2 | 3 | 4 |

**Figure 3: Risk Matrix for a Typical Highway Bridge**

For the risk matrix shown in Figure 3, divisions have been made to separate the bridges requiring more frequent inspections (category I) from those requiring less frequent inspections (e.g. categories III, IV and V). The inspection interval categories are shown in Table 6. Bridges with elements falling in category II require the typical inspection interval of 24 months, currently used under the NBIS.

**Table 6: Maximum Inspection Interval Categories**

| Category | Maximum Interval |
|---|---|
| I | 12 months or less |
| II | 24 months |
| III | 48 months |
| IV | 72 months |
| V | 96 months |

The inspection intervals and the divisions on the risk matrix are engineering-based to ensure a high margin of safety and multiple periodic inspections take place before the likelihood of failure becomes high. In other words, the intervals are determined such that the likelihood of failure remains low and the intervals are further reduced as consequences increase to provide additional levels of safety. For example, the likelihood of a damage mode resulting in a failure is based on a 72 month timeframe. For a given element, if there is low likelihood of a failure (OF = 2), and the consequence of that failure is moderate (CF = 2), the inspection interval of 72 months (Class IV) is identified on the matrix. This is justified, since the analysis has indicated that there is a low likelihood of failure, and even if the failure occurs, there will be only a moderate effect on the serviceability of the bridge. However, if the consequence of the failure were high, then the inspection interval is reduced to 48 months (Class III) and 24 months (Class II) if the consequence is severe. Alternatively, if the likelihood of failure is moderate (OF = 3) over 72 months, the maximum inspection interval is less than 72 months, regardless of the consequence; 48 months if the consequence were only low (benign, CF = 1) or moderate (CF = 2) and 24 months if the consequence is high (CF = 3). Similarly, if the likelihood of failure were remote over the 72 month timeframe, it may be justified to have a maximum interval of more then 72 months, particularly if the consequences are assessed to be benign (CF = 1). As the consequences increase, this interval is reduced.

## <u>Case Studies of the Methodology</u>

Two case studies were conducted to evaluate the effectiveness of the RBI method. The objectives of the case studies were as follows:

- Demonstrate the implementation of the methodologies with state DOT personnel and
- Verify the effectiveness of RBI analysis in determining suitable inspection intervals for typical highway bridges.

The first case study was conducted for a sample of prestressed bridges in Oregon and the second one for steel bridges in Texas. In each case a group of bridge experts were gathered to conduct the RBI analysis during a 1.5 day RAP meeting in the host state. The RAP panels consisted of state department of transportation engineers involved in the inspection, maintenance, and management of bridges within the state.

The RAP meeting consisted of a series of designed expert elicitations intended to develop comprehensive data models for RBI. During the meeting, credible damage modes pertaining to the family of bridges being analyzed were identified through consensus of the RAP. Relevant attributes that contribute to likelihood of those damage modes progressing or occurring were also developed through the designed elicitations. Following the identification of the damage modes and relevant attributes, these attributes were ranked according to their impact on the likelihood for that damage mode (high, medium, or low) as a means of establishing an initial scoring approach. CFs for each damage mode and bridge component are also developed through a designed elicitation and consensus of the panel. Data from the RAP meetings were subsequently analyzed by the research team, organized into scoring models for each damage mode based on the RAP results, and utilized in the back-casting procedure to verify the effectiveness of the RAP results.

In the back-casting procedure, the data models developed by the RAP were applied to individual bridges based on historical inspection records. For example, the data model may be applied to a bridge based on the year 2000 inspection records for the bridge, resulting in an RBI interval that would have been determined in the year 2000, were RBI practices applied at that time. These results were then compared with the actual performance of the bridge, based on the inspection records for the years 2002, 2004, 2006, etc. to determine if the RBI inspection interval would have adequately addressed the inspection needs for the bridge. The criteria for determining the effectiveness of the data model included:

1. Did the condition rating for any component change significantly during the RBI interval in a manner that was not captured or anticipated effectively, but would have been captured (or detected sooner) by a standard, 24-month interval?
2. Were there any significant maintenance or repair actions completed that would have been delayed as a result of implementing an RBI interval (relative to a standard, 24-month interval)?
3. Were there any significant factors or criteria not identified through the RAP analysis that were needed in the data models to provide suitable results?

Overall, the results of back-casting verified that the methodology was capable of determining an effective and safe inspection interval. There were no instances of bridge deteriorating to a serious condition during the RBI inspection intervals recommended using the proposed methodology.

## Conclusions

A reliability-based approach was fully developed and documented through the Guideline. This new inspection paradigm could transform the calendar-based, uniform inspection strategies currently implemented for bridge inspection to a new, reliability based approach that will better allocate inspection resources and improve the safety and reliability of bridges.

The implementation of the Guideline developed through the research was tested by conducting case studies in two states. These studies demonstrated and verified the effectiveness of the procedures developed in the research for identifying appropriate inspection intervals for typical highway bridges. It was shown through these studies that the RBI practices identified appropriate inspection intervals of up to 72 months. It was concluded from these studies that implementation of the RBI practices did not adversely affect the safety and serviceability of the bridges analyzed in the study, based on the analysis of historical inspection records. These studies also demonstrated successfully the implementation of the Guidelines and the procedures by state DOT personnel.

## Acknowledgments

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## References

Washer, G., Nasrollahi, M., Applebury, C., Connor, R., Ciolko, A., Kogler, R., Fish, P., and Forsyth, D. (2014).  *Proposed Guideline for Reliability-Based Bridge Inspection Practices*. NCHRP Report 782. Transportation Research Board of the National Academies, Washington, DC.