Appendix A.
Handbook for Implementation of Risk-Based Inspection (RBI)

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Definitions

Attributes: Characteristics that affect the reliability of a bridge or bridge element.

Condition Attributes: Characteristics that relate to the current condition of a bridge or bridge element. These may include element ratings, component ratings, and specific damage modes or mechanisms that significantly affect an element's reliability.

Consequence Factor: Factor describing the expected outcome or result of a failure.

Damage mode: Typical damage affecting the condition of a bridge element (e.g., spalling of concrete, cracking. etc.).

Delphi process: The Delphi process is a method of expert elicitation that involves consulting a panel of experts through a series of systematic feedback rounds to develop consensus opinions on parameters needed for decision-making. Experts are surveyed anonymously and then consensus is formed.

Design Attributes: Characteristics of bridge or bridge element that are part of the element's design. These attributes typically do not change over time except when renovation, rehabilitation or preservation activities occur.

Deterioration mechanism: Process or phenomena resulting in damage to a bridge element (e.g., corrosion, fatigue, etc.).

Element: Identifiable portions of a bridge made of the same material, having a similar role in the performance of the bridge, and expected to deteriorate in a similar fashion.

Failure: Termination of the ability of a system, structure, or component to perform its intended function (API, 2016). For bridges, the condition at which a given bridge element is no longer performing its intended function to safely, and reliably, carry normal loads and maintain serviceability.

Loading Attributes: Loading characteristics that affect the reliability of a bridge or bridge element such as traffic or environment.

Occurrence Factor: Factor describing the likelihood that an element will fail during a specified time period.

Operational Environment: The operational environment is a combination of the circumstances surrounding and potentially affecting the in-service performance of bridges and bridge elements. These include typical loading patterns, ambient environmental conditions, construction quality and practices, maintenance and management practices, and other factors which may vary between different geographic regions and/or organizational boundaries.

Probability: Extent to which an event is likely to occur during a given time interval (API, 2016). This may be based on the frequency of events, such as in the quantitative probability of failure, or on degree of belief or expectation. Degrees of belief about probability can be chosen using qualitative scales, ranks or categories such as "Remote/Low/Moderate/High" or "Remote/Unlikely/Moderate/Likely/Almost Certain."

Reliability: Ability of an item, component, or system to operate safely under designated operating conditions for a designated period of time or number of cycles.

Risk: Combination of the probability of an event and its consequence.

Risk Analysis: Systematic use of information to identify sources and estimate the risk. Information can include historical data, theoretical analysis, informed opinions and engineering judgment.

Risk Model: A collection of attributes, criteria, and weights used to assess the level of risk.

Screening Attribute: Characteristics of a bridge or bridge element that:

- Make the likelihood of serious damage unusually high,
- Make the likelihood of serious damage unusually uncertain,
- Identify a bridge with different anticipated deterioration patterns than other bridges in a group or family.

A.1. Introduction

This handbook is intended to help develop risk-based inspection (RBI) practices. The scope of the handbook includes Method 2 analysis for RBI intervals for routine inspection (FHWA, 2022a). RBI intervals for routine inspection of highway bridges were included in the latest revision to the NBIS (FHWA, 2022a). The RBIs envisioned by the National Bridge Inspection Standards (NBIS) include two approaches to determining the inspection interval, referred to as Method 1 and Method 2. For intervals up to 48 months, Method 1 has prescribed criteria that must be met, and owners are expected to identify additional criteria based on their experience with the bridges in their inventory. Method 2 analysis involves using a Reliability Assessment Panel (RAP) to develop the risk assessment process and identify criteria for extended inspection intervals of up to 72 months. The process for developing the risk assessment process using Method 2 is described in this document.

A.1.1. Background

Risk is something that individuals live with every day in making decisions. Simple decisions such as crossing a busy street require an assessment and acceptance of risk. Engineers assess risk in formulating designs and maintaining systems. The fundamental concept of risk assessment is to estimate how likely it is for a certain adverse event to occur, and to estimate the potential consequences of that event.

Risk assessment is the process of identifying the sources of hazards, estimating the risk and evaluating the results. Risk assessment processes address three fundamental questions (Washer et al., 2014):

1. What can go wrong?
2. How likely is it?
3. What are the consequences?

Risk-based processes for inspection, maintenance, and asset management have expanded dramatically in recent years to improve the allocation of resources and ensure the safety and serviceability of many diverse types of systems and technologies.

Risk is defined as the product of the probability of an adverse event and the consequence of the event's outcome. This could be expressed generally as(Washer et al., 2014):

$$Risk = Probability\ x\ Consequence$$

Equation A-1. Generalized risk equation.

The probability can be expressed quantitatively as a *probability of failure* (POF) when suitable data is available, or qualitatively (i.e., *high*, *moderate*, *low*) based on expert judgement, to estimate *likelihood of occurrence* for a certain adverse event. *Consequence* is a measure of the event's impact, which may be expressed in terms of safety, serviceability, economic, or environmental impacts. The consequence can also be expressed quantitatively or qualitatively. Presenting risk qualitatively is frequently an effective method of illustrating risk, especially for complex systems or where suitable quantitative data is unavailable.

The definition of "failure" adopted for risk analysis of bridges is as follows: *the condition at which a given bridge element is no longer performing its intended function to safely, and reliably, carry normal loads and maintain serviceability* (Washer et al., 2014). This condition is deemed to be analogous to condition rating (CR) 3, Serious condition, for the purposes of the risk analysis (FHWA, 2022c; Washer et al., 2014). The definition of CR 3 is provided in the Specifications for the National Bridge Inventory (SNBI) as "*Major* *defects; bridge or approach roadway is seriously threatened. Condition typically necessitates more frequent monitoring, load restrictions, and/or corrective actions."* (FHWA, 2022c)

The primary objective of the risk analysis is to prioritize bridges in terms of their inspection needs by considering the factors that affect the likelihood that a given bridge will deteriorate significantly in the next 72-months, and the potential consequences.

The overall process intends to prioritize bridges in terms of inspection needs and sort existing bridge inventories into groups in a systematic way. The general prioritization for routine inspection of bridges is shown Figure A.1. Based on engineering judgment and experience managing bridges since the inception of the NBIS, most CR ≥ 7 bridges are expected to have very small likelihoods of deterioration to a CR 3 in the next 72 months. Bridges with components in CR 6 have a higher likelihood as compared with CR ≥ 7, and bridges with components in CR 5 have a higher likelihood than bridges with CR 6. This leads to a general prioritization as shown in Figure A.1.

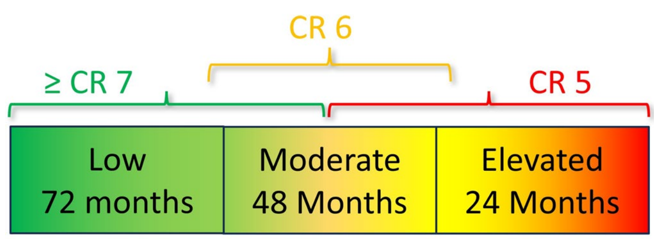


Figure A.1. Prioritization for routine inspection of bridges.

This assessment leads to target ranges that can be used to analyze risk models based on expert judgement to ensure the attributes and criteria in the risk models produce results consistent with this assessment. One of the risk models' purposes is to identify those bridges or components that may not match this assessment. For example, a CR 7 component that has poor durability characteristics and evidence of emerging damage that indicates its deterioration is progressing at an increased rate as compared with other CR 7 bridges. Overall, the purpose of the risk assessment is to simply place a given bridge into one of the three general categories represented in Figure A.1.

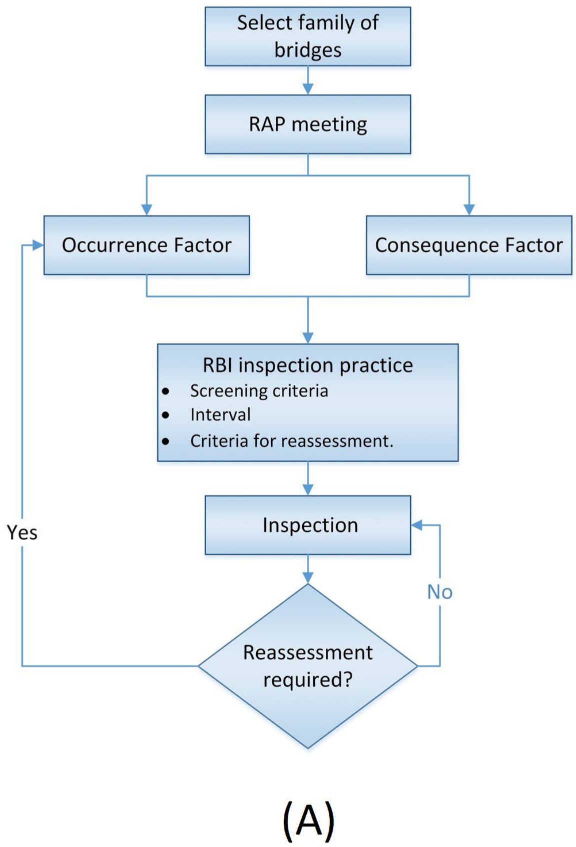
A.2. Overview of the RBI Process

The overall process for implementing RBI analysis is shown in Figure A.2 (A). The first step of the process is to determine the family of bridges for which a risk analysis is to be developed. A family of bridges is a group of bridges constructed of similar materials and deterioration patterns when placed in similar operational environments. Once a family of bridges is selected, a RAP can be formed of individuals with "*collective knowledge in bridge design, evaluation, inspection, maintenance, materials, and construction*" relevant to the subject family of bridges (FHWA, 2022a).

Risk analysis for RBI has two primary components – an estimate of the likelihood of serious damage (i.e., CR 3) developing in the next 72 months, and an assessment of the potential consequences. The likelihood of serious damage occurring is estimated based on an Occurrence Factor (OF), which is a measure of the relative likelihood of damage based on expert judgement and a semi-quantitative scoring process. The OF is estimated based on *attributes* of bridge components, which are characteristics of a bridge component that affect its reliability.

The Consequence Factor (CF) measures the consequence of different damage modes in bridge components. The CF is estimated based on the effect of the damage on the ability of the component to safely, and reliably, carry normal loads. Typically, the CF is determined based on attributes such as the redundancy of the structure, load capacity, service level, and feature under the bridge.

The risk matrix shown in Figure A.2 (B) is used to identify the specific interval for a given bridge based on the OF and CF found through the analysis. The damage modes identified for assessing the OF are scored using attributes and criteria developed through RAP meetings. Attributes associated with the consequence of each damage mode are used to estimate the CF. These two factors are combined to locate a particular bridge component on a risk matrix to determine the appropriate inspection interval for a bridge.



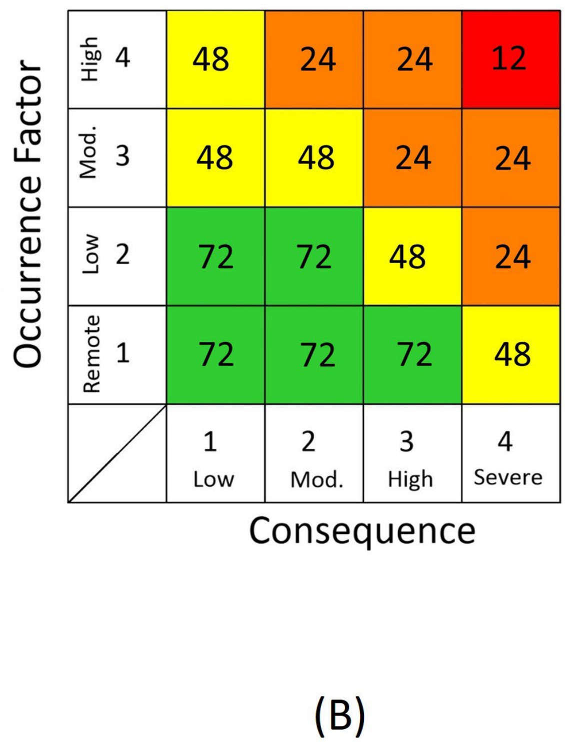


Figure A.2. Overview of the RBI process (A) and risk matrix (B) showing inspection intervals (months).

A.2.1. Soliciting Expert Judgement

The RBI process relies on expert judgements provided by a RAP that identify attributes and criteria for analyzing risk. The process for expert elicitation of the RAP is based on a Delphi process that has the goal of obtaining objective judgements from the panel. The Delphi process is a means of aggregating expert opinion through a series of structured questions in order to obtain expert knowledge in areas where available data is limited (Gunaydin, 2006; Kiral, Kural, & Çomu, 2014). The Delphi process consists of anonymous surveys of experts followed by consensus development to form an expert solution to the given problem. The anonymous nature of the initial surveys intends to avoid bias introduced by certain group dynamics, such as vocal or strongly opinionated participants dominating the discussions.

The process for a Delphi survey includes defining a problem, developing questions for experts to resolve, selecting suitable panel members, providing open-ended questions for the experts to provide anonymous input, and controlled assessment and feedback (Hohmann, Brand, Rossi, & Lubowitz, 2018). The assessment of feedback portion consists of aggregating the anonymous survey results and forming additional rounds of questions (or scenarios) that are presented to the experts in a group setting to develop consensus opinions or judgements from the initial anonymous results.

The Delphi process is used to structure expert elicitations from the RAP to identify credible damage modes and attributes for bridge components. Exercises are formatted to allow for the individual RAP members to provide input and use those inputs to form consensus on the damage modes and attributes to be assessed in the risk analysis process.

A.3. RBI Implementation

A.3.1. The RAP Meeting

The RAP meeting is a central tool in the risk analysis process. The RAP is a panel formed at the owner level. The reason the RAP is formed at the owner level is because the performance of bridge elements and components vary widely across the overall bridge inventory due to differences in ambient environment, policies and practices, history, and experience. The RAP is intended to gather expert knowledge of those most familiar with the operating environment in which the bridges exist. The objectives of the RAP meeting are as follows:

1. Characterize the OF based on expert judgement.
    a. Determine credible damage modes.
    b. Identify and prioritize key attributes that impact the reliability of bridge components or elements.
    c. Develop criteria for rating the attributes.
2. Assess the likely consequence scenarios and categorize the CF.

The primary activities of the RAP are shown in Figure A.3. For the family of bridges to be analyzed, the RAP will assess each of the three primary components of the deck, superstructure, and substructure. For each component, the RAP identifies credible damage modes and attributes that impact the reliability of the component. Criteria are developed for each attribute to assess the level of impact on the qualitative scale of *very high*, *high*, *moderate*, or *low*. These criteria are assigned scores based on their impact and a weighted sum model is used to provide a semi-quantitative analysis of the OF. The combination of attributes, criteria, and weights used to assess the OF are termed a *risk model*. The RAP also assesses the appropriate CF for each damage mode based on attributes such as traffic volumes, redundancy, and load capacity.

The following sections will describe each step for the RAP meeting, starting with the selection of the family of bridges, the composition of the RAP, and the role of the facilitator. The mechanics of the exercises used to obtain expert judgement from the RAP members is also described.

A.3.2. Bridge Families

The first step in the risk analysis is to select the family of bridges to be analyzed by the RAP. A “family” of bridges is a population of bridges of similar material of construction, design characteristics, and expected deterioration patterns. For example, a family of bridges may be defined as those bridges with superstructures comprised of prestressed concrete (PSC) beams with reinforced concrete (R/C) decks, or bridges with steel beams and R/C decks. Other design characteristics that are expected to have different deterioration patterns or present different risks can also be used to define the family of bridges to be analyzed. For example, bridges with adjacent PSC box beams may be identified as a different bridge family than PSC beams that are open shapes, if experience has shown the box beam deteriorate differently than the open shapes.

The RAP analysis will identify unique features of portions of the bridge family that should be screened from the risk analysis. Certain bridges that are likely to have different deterioration patterns than other bridges in the family, or if there is experience that indicates certain features are problematic, the screening process can be used to eliminate those bridges from the bridge family considered in the risk analysis. For example, a family of steel bridges with open members may include structures with pin and hanger connections that the RAP may choose to screen from the risk analysis. Therefore, identifying the family of bridges to be analyzed does not need to consider every potential difference between bridges within the family. Table A.1 provides an example of bridge families based on the Specifications for the National Bridge Inventory (SNBI) and the Recording and Coding Guide (NBI) codes for bridges (FHWA, 1995, 2022c). This table shows the SNBI identifiers for span materials and span type that could be used to identify a family of bridges. For example, the steel family of bridges includes open shapes and does not include truss bridges or arches, which are less common and may experience different deterioration patterns and/or consequences resulting from damage as compared with other bridges in the family.

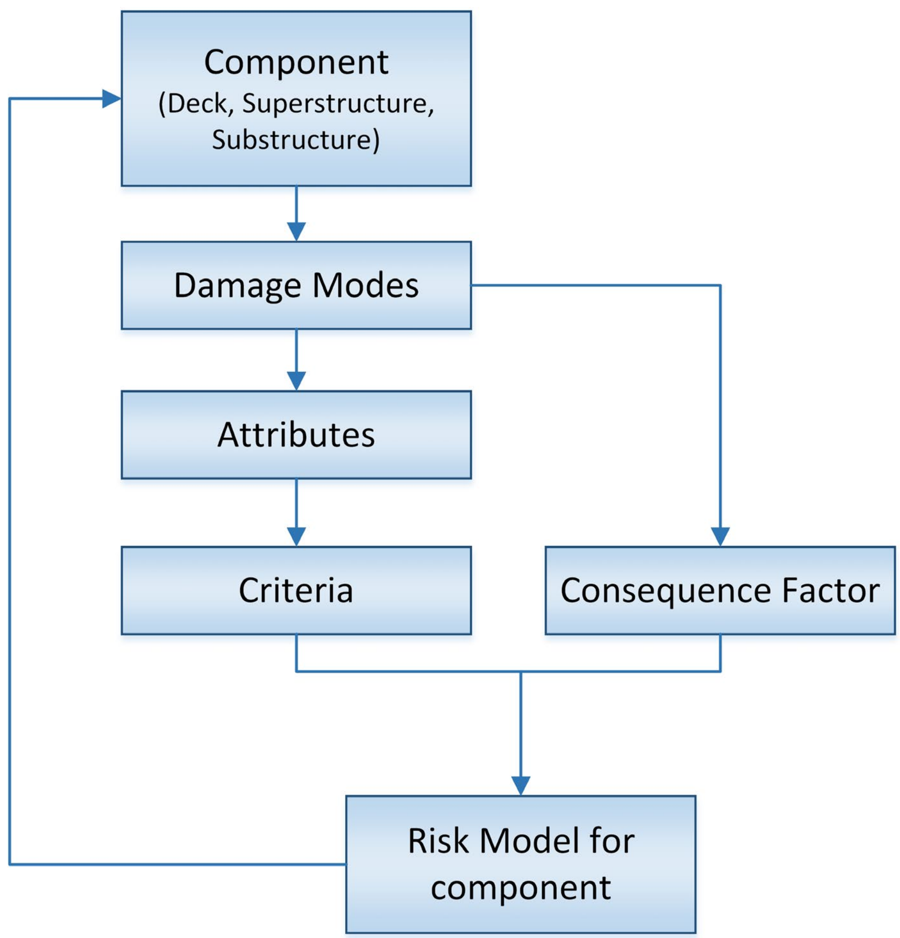


Figure A.3. Flow chart for a RAP meeting.

Table A.1. Example of SNBI items and NBI codes for PSC and steel bridge families.

	SNBI Item ID NBI Code	PSC	Steel
Span Material	B.SP.04 43A	C03 5, 6	S01 – S05 3, 4
Span Type	B.SP.06 43B	G01 - G03 02	G01, G02 02

Once the family of bridges is selected, a RAP meeting should be organized. The following section describes the selection of individuals to participate in a RAP and the requirements for participants.

A.3.3. Identifying RAP Members

The RAP panel is engaged to conduct a risk analysis for bridges based on expert judgement. Individuals with experience operating and managing bridges within a specific inventory of bridges are needed because design features, construction specifications, materials, environment, and bridge management practices differ from one jurisdiction to another. The members of the RAP should be familiar with the operational environment of the inventory of bridges being evaluated.

The RAP typically will consist of four to six experts from the bridge-owning agency. The membership of the RAP is defined by the NBIS as follows: "*The RAP must be comprised of not less than four people, at least two of which are professional engineers, with collective knowledge in bridge design, evaluation, inspection, maintenance, materials, and construction, and include the NBIS program manager.*" (FHWA, 2022a, 2022b) The panel would typically consist of individuals meeting the descriptions shown in Table A.2. A bridge inspection team leader can fill the need for an inspection expert. The NBIS program manager is required. Maintenance and materials engineers that have a familiarity with the deterioration patterns for bridges within the jurisdiction where the analysis is being conducted may be members. Independent experts such as consultants active in addressing maintenance and repairs may also be suitable for the RAP panel. Academics that have conducted research projects that examined deterioration patterns for the family of bridges being considered are also suitable members for the RAP meeting. At least two of the members are required to be registered Professional Engineers.

Table A.2. Listing of potential RAP members.

Position	Position	Position
Bridge Inspection Expert	Bridge Maintenance Engineer	Independent Experts / Consultants
State NBIS Program Manager	Materials Engineer	Academic Experts (with experience with the subject inventory of bridges.)
Bridge Management Engineer	Structural Engineer	Academic Experts (with experience with the subject inventory of bridges.)

A.3.3.1. RAP Facilitator

A facilitator is needed for the RAP meeting to present the scenarios to participants, record results of the individual assessments, and prod participants for input. The facilitator should have considerable experience with the inspection and performance of bridges to assist the RAP with gaining consensus and interpreting input from individual RAP members. One key role of the facilitator is to aggregate the inputs from RAP members, which may include many different terms for the same or related items. For example, RAP members may describe the attribute of rate of deicing chemical application as “salt application”, “chloride level”, “NaCl,” or “deicing chemical application rates.”

A.3.4. Damage Modes

The first activity for the RAP is to identify the credible damage modes for the primary components of deck, superstructure, and substructure. The Delphi process is applied for identifying the damage modes and attributes for a given component. The inquiry's objective is to identify the primary damage modes that are likely to lead to a component failure (i.e., CR 3) and identify other damage modes which may occur but are rare or unique. For the former, the primary damage modes are identified such that risk models can be developed to address the likelihood of that damage mode occurring and causing the component to deteriorate to CR 3. For the latter, the damage modes are considered as potential screening criteria or deemed insignificant and neglected.

To identify damage modes, the anonymous survey seeks responses the question:

- “*If it was reported a [component] is rated as CR 3, based on your experience, what damage would be present in the [component] that has resulted in the low condition rating.”*

The “component” in the question is either the deck, superstructure, or substructure. The individual anonymous assessments for damage modes are conducted using a simple bubble sheet where participants are asked to provide an estimate of the likelihood for each damage mode they identify. An example portion of the bubble sheet is shown in Table A.3, with only two rows shown to illustrate the appearance of the sheets. The actual sheets should provide the RAP members with additional rows to record their input. The bubble sheet includes a space for the RAP member to input damage modes (shown in Table A.3 as hand-written by a RAP member) and circles representing different likelihoods or probabilities associated with the damage mode. The members are instructed to list the damage modes they believe are most likely to cause a given component to deteriorate to CR 3 and provide an estimate of the relative likelihood of the damage mode being the cause of the damage. This provides an independent assessment of the relative priority of the damage modes to identify the damage modes that are likely and those that are unlikely. This exercise helps to identify common damage modes that are likely to occur and prevent bias toward damage modes that are rare or have occurred recently.

The survey results are then aggregated by the facilitator by listing each of the damage modes identified in the survey on a white board, paper charts, or a computer display, and recording the likelihood estimates provided by the RAP members. These data are then reviewed by the RAP and discussed to form a consensus on the most likely damage modes for the given component. The consensus process seeks to determine if a risk model is needed for the damage mode, if the damage mode is suitable as a screening criterion, or if the damage mode is too rare or unique to require consideration in the risk analysis.

Table A.3. Example of a portion of the table provided to RAP members for assessing likely damage modes.

Damage Mode	Likelihood (in 10% increments)									
Delamination and spalling	○	○	○	○	○	●	○	○	○	○
Impact	○	○	○	●	○	○	○	○	○	○
Proportion	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%

The survey results can be summarized in two ways: collecting the individual bubble sheets or asking the panel members for their input. A summary of the results is presented to the RAP in a format that indicates the RAP input in terms of damage modes and likelihoods. The damage modes are well-known and testing of the RAP process has found that the common damage modes are identified through this process quickly. An example from the research is shown in Table A.4 for a steel bridge member. As shown in the table, the most likely damage predicted by the RAP was section loss due to corrosion. Fatigue cracking was also identified as a common damage mode, though much less likely than corrosion damage, according to the RAP input. Impact or collision was also identified by most of the panel. It should be noted that because the exercise is completed individually, not every panel member identifies each damage mode. For example, six panel members identified section loss with a measurable likelihood, but only one member identified movement or bearing issues. A panel member also identified connection issues as a possible damage mode, but the likelihood was estimated to be less than 10%. Discussion should include:

- Are there damage modes identified that have similar characteristics and can be combined?
- Are any of the damage modes very rare, unique, or caused by construction errors?
- Are there any of the damage modes that, if present, should result in a bridge being screened from the RBI process?

The process is intended to identify the key damage modes to be assessed by the RAP. The next step in the process is to identify attributes for each damage mode, as described below.

Table A.4. Example of RAP results for damage modes in steel girders.

Damage Modes	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Section Loss	-	-	-	1	-	1	-	4	-	-
Fatigue Cracking	2	2	1	-	-	-	-	-	-	-
Impact / Collision	4	1	-	-	-	-	-	-	-	-
Connection Issues	-	-	-	-	-	-	-	-	-	-
Movement / Bearing Issues	1	-	-	-	-	-	-	-	-	-

A.3.5. Attributes

A key element of the RBI process is to identify attributes that affect the reliability of bridge elements or components. The attributes are divided into groups for organizational purposes as follows:

- Screening attributes: Attributes that make the POF unusually high or unusually uncertain such that the bridge should be screened from the RBI process.

- Design Attributes: Characteristics of bridge components or elements that are part of its design. These attributes typically do not change over time except when renovation, rehabilitation, or preservation activities occur.
- Loading attributes: Loading characteristics that affect the reliability of a bridge or bridge element such as traffic or environment.
- Condition Attributes: Characteristics that relate to the current condition of a bridge component element. Condition attributes are typically assessed based on inspection data.

A listing of common attributes is described in Appendix D of this report. Several examples are shown Table A.5. The table includes examples of screening attributes such as the CR of components and CS of elements, load rating factors, and Constraint-Induced Fracture (CIF) details. Design attributes, loading attributes, and condition attributes are also shown.

Table A.5. Examples of Screening, Design, Loading, and Condition attributes.

Screening Attributes	Design Attributes	Loading Attribute	Condition Attributes
CR ≤ 4, CS = 4	Corrosion Protection Level	ADT / ADTT	CR / CS
Load Rating Factor < 1.0	Minimum Vertical Clearance	Rate of Deicing Chemical Application	Joint Condition
CIF Details	Feature Under	Subjected to Overspray	Bearing Condition
Fatigue Cracking	Age of Component	Likelihood of Overload	Coating Condition

A.3.6. Soliciting RAP for Attributes

Once the damage modes are prioritized, the key attributes that affect the component's reliability in terms of the specified damage mode are addressed. For each of the key damage modes, the RAP members are presented with a second survey question to independently identify attributes. For example, the panel is presented with the question:

- "*For the [component, e.g., steel girder), estimate how long will it be before significant [damage mode, e.g., section loss] develops? What information do you need to know to make that estimate?*"

This survey question intends to elicit objective input on the key attributes to be considered in the risk model. The question is formed in a manner expected to be familiar to engineers with experience in the condition assessment and maintenance of highway bridges. The question's objective is to identify and rank attributes that significantly impact the development and progression of the subject damage mode.

The RAP members are asked to rank the impact of the attribute on a qualitative scale of *high*, *moderate*, or *low*. These data are used as a basis for developing consensus on the priority rank of the attributes through discussion with other RAP members. In this way, the most significant attributes are identified and provided a rank used to develop a scoring scheme for the risk model. An attribute worksheet should be used for recording the independent input from the RAP members.

Once each RAP member has provided their inputs on the attributes, the facilitator should aggregate the results by listing the individual attribute identified and the rankings provided by the RAP members. Table A.6 shows an example of RAP inputs aggregated by the facilitator. The table lists the attributes identified by RAP members and their input on the appropriate rank of the attributes each has identified. This forms the basis for discussion of which attributes should be included in the risk model and how they should be ranked.

Table A.6. Example listing of attributes and rankings.

	High	Moderate	Low	Screening
Coating Condition	5	0	0	0
Salt application	4	1	0	0
Joint condition	4	1	0	0
Deck drainage	0	2	3	0
Deck type	0	3	1	1
Deck condition	1	3	1	0
Overspray	1	2	1	0

The tasks for the facilitator include:

- Discuss what was intended by any attributes that are not clear or require interpretation. For example, "Deck type" was identified by several RAP members because timber decks or steel grating allow drainage directly onto the superstructure.

1. Discuss if any of the attributes may be suitable screening criteria that identify bridges with deterioration patterns that may be significantly different than common bridges in the subject bridge family. For example, the attribute of "deck type" is intended to discriminate R/C decks with typical drainage systems from open decks (e.g., grating or timber decks) that allow drainage directly onto the superstructure, which will accelerate the deterioration of the superstructure member. This attribute may be identified as a screening criterion to simply screen any bridges with a grated or timber deck from the analysis, since the deterioration patterns for these bridges are likely to be different than for bridges with R/C decks.
2. Develop consensus on the relative significance of each of the attributes to finalize the ranking of each attribute as *high*, *moderate*, or *low*. This discussion may result in a particular attribute being assigned a ranking of *very high* if its impact is much greater than the other attributes identified.

The ranking of the attributes provides the initial relative weights for the different attributes, with attributes ranked as *high* being assigned 20 points, those ranked as *moderate* assigned 15 points, and those ranked *low* being assigned 10 points. If any of the attributes are identified as *very high*, 30 or 40 points may be assigned for scoring in the risk model. The RAP may select different values than those indicated here to reflect their expert judgment on the relative weights or importance of the attributes they identify. Once the attributes have been ranked, criteria need to be developed to score the risk model.

A.3.6.1. Criteria for Attributes

Once the attributes have been ranked, group consensus building is used to identify criteria for scoring each attribute. The criteria are intended to characterize the attribute for a bridge. For example, for the damage mode of section loss in steel girders, the attribute of coating condition may be identified as an attribute with a rank of *high*. If the coating is in good condition, then the coating condition will not increase the likelihood of corrosion damage developing. If the coating is failing, exposing the steel to the corrosive environment, then it will have a significant impact on corrosion developing and resulting in section loss. Criteria are developed for rating each attribute. For example, if the coating is failing as indicated by, for example, 20% or more of the coating being rated in CS 3, the attribute will be rated *high*. If the coating is in good condition, e.g., 100% of the coating is in CS 1, the attribute will be rated *low*. Specific criteria obtained from available records and data are preferred to assist with later risk model analysis.

“Surrogate” data can be used to rate attributes as needed. As used herein, “surrogate” refers to specific data that can be used to either infer or determine other data that are needed. For example, using the element CS to capture different precursors to damage such as cracking in concrete. Although the CS assigned during an inspection may not be assigned solely due to cracking, it could be assumed cracking would be captured by the CS assessment if it was present. Engineering judgement should be used to identify appropriate surrogates for attributes.

A.3.6.2. Categorical Models

Some damage modes have very few attributes that affect the likelihood of serious damage developing in the next 72 months. For example, the likelihood of impact damage due to over-height vehicles depends only on the vertical clearance and if there is a roadway below the bridge. Therefore, scoring such a model is not necessary, since there are very few different combinations of attributes that define the likelihood of the event occurring. For these instances, attributes and criteria can be assigned to the *remote*, *low*, *moderate*, or *high* OF category. For example, the likelihood of impact from an over-height vehicle depends primarily on vertical clearance of a bridge and may be considered more likely when traffic volumes are high on the roadway below. Since there are only two attributes to consider for bridges over roadways, vertical clearance, and ADT (Average Daily Traffic), the OF can be determined by categories – e.g., bridges with vertical clearance of 14 ft or less are categorized as *high*, and bridge with 16 ft or more of vertical clearance are categorized as *remote*. Bridges with 14 to 16 ft of clearance may be categorized as *moderate* when ADT is high and *low* when ADT is low. The specific criteria should be developed by the RAP based on expert judgement and experience with the operational environment of the bridge family being considered.

A.3.6.3. Documentation of RAP Risk Models

These RAP results can be transcribed into flowcharts to illustrate the framework of the risk model. The flow charts show the damage modes, attributes, and criteria for each damage mode identified by a RAP. The rank of each attribute is also listed. The flowcharts organize the RAP results in a systematic fashion and summarize the outcome of the RAP surveys. This type of flow chart can be used to summarize the results in a form amenable to computer programming or for review.

A partial flow chart for bridge deck attributes and criteria developed during a RAP meeting is shown in Figure A.4. The figure shows only a portion of the flowchart for the damage mode of delamination and spalling in a bridge deck. The figure shows four of the attributes identified by the RAP and the rank assigned to each attribute. The attribute of “Current Condition Rating” and “Spalls and Patches” were each ranked as *high* (H) by the RAP. The attribute of “Rate of Salt Application” was ranked as *moderate* (M), and the attribute of “Corrosion Protection Level” was ranked *low* (L). Criteria for each of these attributes were also identified as shown in the figure. For the attribute of “Current Condition Rating,” the criteria were described in terms of the CR for the deck. For the attribute of “Spalls and Patches,” the criteria for the attribute were described in terms of the element CS from element level inspection. The CS for this element considers the presence of spalling, patches, and cracking in the deck and acts as a surrogate for the “Spalls and Patches” attribute. In this way, the data available from element – level inspection can be used to support a data-driven process for risk assessment. Although the CS is not precisely the same as the RAP input it was deemed a practical surrogate. In a similar way, the rate of salt application, which is rarely data that is available state-wide, is expressed in terms of available data such as ADT values and functional class of the roadways that commonly receive more (or less) aggressive deicing treatments.

A.4. Consequence Factor

The CF considers the potential outcome from component deterioration and failure according to the definition of failure given by the NCHRP 782 report, "*the condition at which a given bridge element is no longer performing its intended function to safely, and reliably, carry normal loads and maintain serviceability.*"(Washer et al., 2014) This is a broad definition that must be interpreted to identify the appropriate CF to apply to different situations or scenarios under which a failure event may occur. The CF is used to categorize the outcome or result of *failure* (i.e., CR 3) of a bridge element or component due to a given damage mode. It should be noted that it is not envisioned that the component will be allowed to deteriorate to CR 3 before being inspected. The CR 3 rating of the component is used as a reference point for prioritizing damage modes in terms of the potential risk. The CF categorizes the consequence as one of four categories – *low*, *moderate*, *high*, or *severe*.

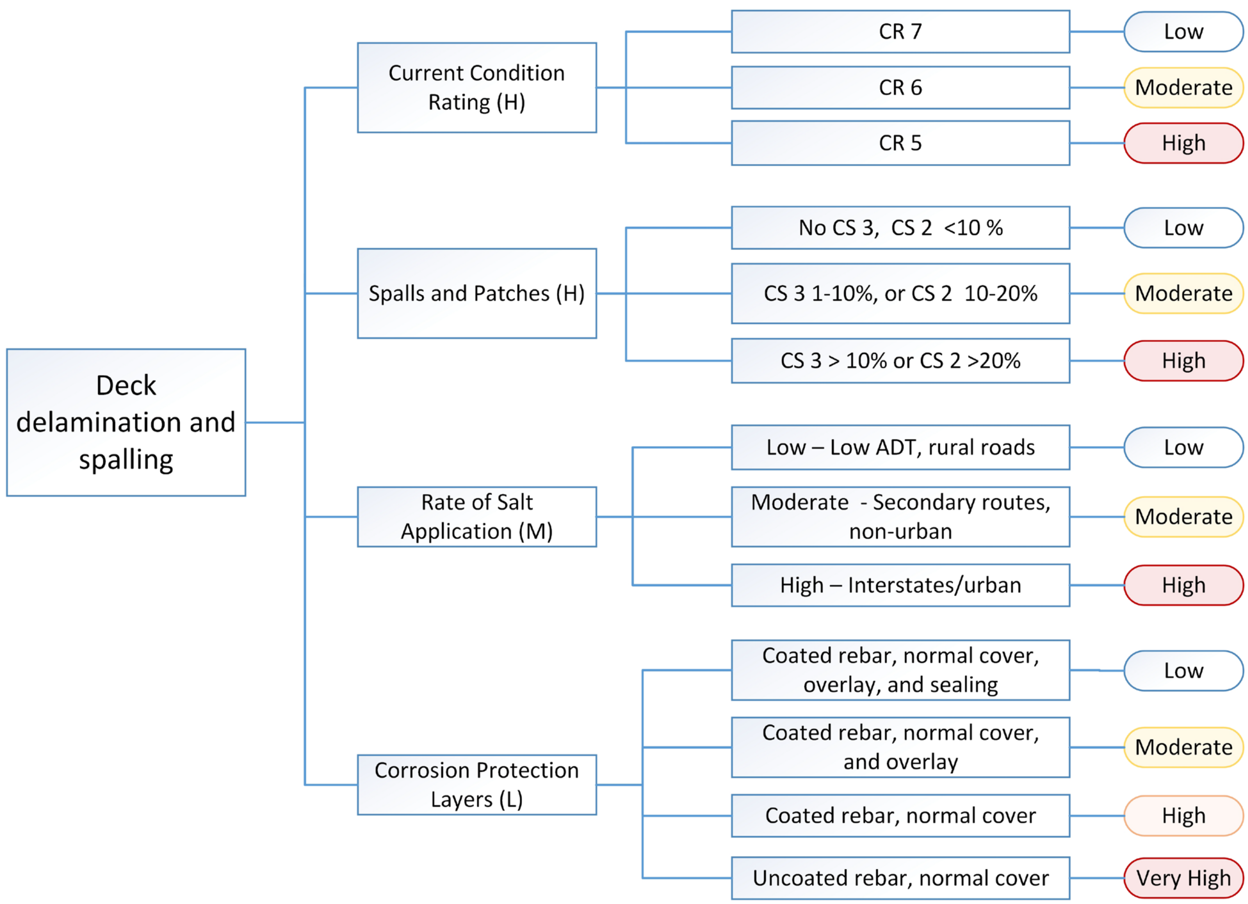


Figure A.4. Typical flow chart for RBI showing attributes, ranking, and criteria.

General descriptions of the CF are described in NCHRP 782 to provide a framework for categorizing the CF. Table A.7 shows the framework from the NCHRP 782 report. The CF is intended to characterize the immediate or near-term effect of CR 3 damage to a component. Many damage modes can result in reduced long-term durability of a component that can later lead to complete structural failure if unaddressed. But that is not what occurs in the near-term; it may take years for damage to further develop to the point where the capacity of the component is totally lost. The assessment of the damage by the RAP should only consider, conservatively, the immediate or near-term impact when the component is first rated in CR 3. Existing policies and practices as well as experience with previous instances of CR 3 components should be used in considering the appropriate CF for a given scenario.

The NCHRP 782 report lists the following attributes that should be considered for the CF:

- ADT / ADTT.
- Feature under the bridge.
- Feature carried.
- Redundancy.
- Load carrying capacity / load rating.

The NCHRP 782 report also lists composite construction and use of stay-in-place forms as potential attributes to be included in the CF. Members that are composite with the deck of the bridge have additional redundancy as compared with non-composite design. Stay-in-place forms provide some protection against concrete falling from a damaged deck into traffic below because the form will contain the material, assuming the form itself is not severely deteriorated. These attributes could be considered for inclusion as CF attributes if deemed appropriate by the RAP.

Table A.7. General description of the CF 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

A.4.1. Example CF Attributes

A categorical model can be used for the CF to address the consequences of a component in a bridge deteriorating to a CS 3. A categorical model differs from the risk model used for the OF because rather than using a semi-quantitative scoring approach, attributes and criteria are used to simply define the CF categories of *low*, *moderate*, *high*, or *severe*. Attributes such as load capacity, redundancy, serviceability, and the features under the bridge are typically included. The RAP should develop appropriate criteria for a given bridge inventory and may identify other attributes that should be considered. Example attributes are discussed in the following paragraphs.

Figure A.5 shows example criteria that could be used for categorizing redundancy and load capacity attributes. The redundancy factor assigns non-redundant structures as potentially having a *severe* consequence, while redundant structures would be placed in the category of *moderate* or *low*. Structures that would be assigned to the *high* category are structures with redundancy that may require analysis to establish or be subject to owner policies. For example, bridges with only three members or bridges with large beam spacings may be considered nonredundant based on an owner’s policy or may require analysis of the role of composite behavior and secondary members to ensure redundancy. The load capacity attribute categorizes bridges in terms of the inventory load rating for the bridge, with the *severe* category assigned to bridges with an inventory Load Rating Factor (LRF) of less than 1.0. Bridges with a LRF of greater than 1.2 are assumed to have reserve capacity and are categorized as having a CF of *low*. Bridges with an LRF of 1.0 to 1.2 are categorized as having *moderate* CF for most cases. Other factors such as frequent exposure to overloads or permit load limits may elevate the CF for a certain bridge to *high* based on engineering judgement. These attributes and criteria are exemplary; the RAP should assess appropriate attributes and criteria for the subject bridge family and operational environment.

Example factors that consider the safety and serviceability of the bridge are illustrated in Figure A.6. The serviceability factors consider the traffic volume to determine the potential consequence resulting from a lane closure due to either loss of a primary member in a redundant bridge, or serious damage in a bridge deck that affects traffic safety and serviceability of the deck. The levels of ADT shown in the figure were subjectively selected based on expert judgement. The ADT levels vary significantly between different states, and as such this attribute was described in percentiles. The goal is to identify bridges where lane closures present a significant consequence in transportation efficiency. The factor also considers the detour length for bridges that are essential to the transportation network. The criteria indicate that essential bridges with large detour routes may have a high consequence, and if the ADT levels are also elevated, the CF may be considered severe. Again, these criteria are examples and input from the RAP should be used to determine if such criteria are needed, and the specific ADT and detour lengths that should be applied.

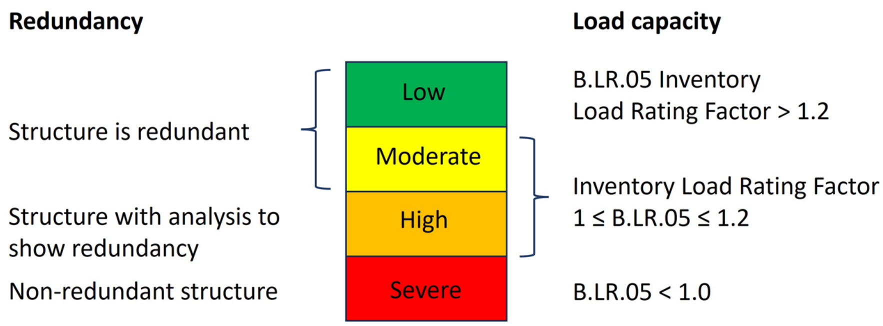


Figure A.5. Example CF attributes for redundancy and load capacity.

Finally, the CF includes attributes to consider the possibility that a deteriorated component may result in concrete falling into traffic below the bridges. This factor considers that two events must occur for falling debris to impact a vehicle directly. First, debris must fall from the bridge, and second, a vehicle must be present to be impacted. Consequently, this factor considers the features under the bridge and the ADT level. Again, the ADT level is expressed in percentile terms and was subjectively chosen based on expert judgement.

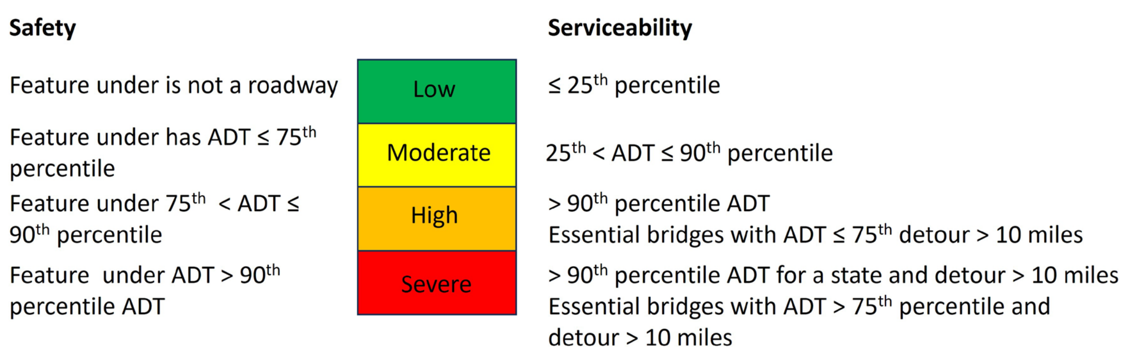


Figure A.6. Example CF attributes and categories for safety and serviceability.

The highest relevant CF for a given damage mode should be used in the risk analysis. It should be noted that most of the criteria for the CF attributes are based on engineering judgement, and users may wish to modify the factors appropriately for their bridge inventories and operational environments.

A.4.2. Consequence Scenarios

The RAP develops attributes and criteria for the CF comparable to how the damage modes and attributes were developed. The RAP considers the scenario that may be anticipated when one of the damage modes being analyzed progresses to a serious condition (CR 3). The consequence scenario considers both the damage mode and scenario presented by the damage. For example, if the bridge is located over a roadway or railway, consequences associated with falling debris may need to be considered, while bridges over unoccupied parcels of land do not need to have this potential consequence considered. The exercise's objective is to identify the attributes to be considered in the analysis of the CF for each damage mode and determine appropriate criteria.

The RAP is presented with a description of a typical bridge within the bridge family being considered. For example, if the bridge family is PSC bridges, the RAP may be presented with the scenario:

- *Scenario: A multi-girder prestressed bridge has a maximum span length of 65 ft, the overall bridge length is 120 ft. The deck consists of a cast-in-place RC deck with an integral wearing surface. The piers have a concrete pier cap on pier columns. Abutments are reinforced concrete.*

The scenario is presented with limited information to provide the opportunity for discussion of the factors that may need to be considered in the analysis. Photographs of an example bridge and relevant components with significant damage can be used to provide context for the RAP. The RAP should consider all damage modes identified for the family of bridges and provide input on the likely CF based on expert judgement. The RAP should consider the immediate or near-term effect of the subject component being rated as CR 3. Responses can be recorded on bubble sheets such as that shown in Table A.8.

The RAP is asked to consider each damage mode identified in the assessment of the OF. The responses of the RAP are aggregated by the facilitator for discussion. The RAP then discusses the factors (i.e., attributes) that would influence the responses they provided. The attributes that would affect their responses include redundancy of the bridge, the feature under the bridge, ADT, etc. The RAP should also be surveyed to determine criteria for the attributes. For example, what ADT level should be considered sufficient to categorize the CF as *high*? If a bridge deck were rated in CR 3, what would be the immediate or near-term actions taken? Would the bridge be closed, resulting in a major serviceability effect? Or would the deck be programmed for rehabilitation? Obviously, the response to these questions depends on the scenario surrounding the event. If the ADT on the deck was relatively high, expedited repairs requiring a lane closure may be the response. If the deck experiences especially high ADT, it may represent a major effect on serviceability because the repairs will cause a significant disruption in traffic. If the bridge has both very high ADT and has a long detour length, meaning reasonable alternate routes are not available, that might be considered a *severe* consequence. If the bridge has low ADT, the response may be to program the deck for rehabilitation and the CF would be *low*.

Table A.8. Example CF bubble sheets for RAP input.

Category	Descriptive definition	Likelihood (%)
Low	Minor effect on serviceability, no effect on safety	○○○○○○○○○○
Moderate	Moderate effect on serviceability, minor effect on safety	○○○○○○○○○○
High	Major effect on serviceability, moderate effect on safety	○○○○○○○○○○
Severe	Structural collapse / loss of life(major/major)	○○○○○○○○○○

The RAP input should also determine if there are any other factors that should be considered in the analysis of the CF. Typically, the factors identified by the RAPs would be those listed above. However, other attributes may be identified by the RAP that are either local, such as particular bridges or bridges along a certain critical corridor that should be treated differently because they are essential bridges.

A.4.3. Application of CF

The CFs attributes and criteria are appropriately applied by considering the scenario presented by each damage mode in the analysis. For example, damage modes for bridge decks would typically consider the Serviceability and Safety CF attributes as shown in Table A.9. Superstructure damage modes that may result in reduced load capacity requiring a lane closure would consider Redundancy, Load capacity, and Serviceability. The purpose of applying the CF in this way is to apply the appropriate CF to each damage mode. For example, the risk assessment of the deck should not rely on the redundancy of the superstructure.

Table A.9. Example of damage modes and associated CFs.

Component / element	Damage Mode	Applicable CF
Deck	Delamination and spalling	Safety Serviceability
Superstructure	Cracking / fracture	Redundancy Load Capacity Safety Serviceability
Superstructure	Impact damage	Redundancy Load Capacity Serviceability
Substructure	Delamination and spalling	Serviceability

A.4.4. Training for the RAP

The risk analysis uses processes intended to simulate typical decision-making used by engineers regarding the urgency (or lack of urgency) of repair and maintenance activities. However, the processes used in the risk analysis are more formalized and require consensus building. Training of RAP members in preparation for the meeting is needed to clearly state the objectives of the RAP meeting, describe the underlying process to be used, and set the stage for the RAP members to provide valuable input to the analysis conducted. A training session prior to the meeting should include:

1. The overall approach to risk analysis that needs to be implemented.
2. Definitions and examples of attributes and attribute criteria.
3. Consideration for assigning criteria to an attribute.
4. Objectives and examples of the exercises conducted during the RAP meeting.
5. Example risk models and CF attributes.

A.5. Analyzing the Risk Model

This chapter describes how to analyze the results of the risk models developed by the RAP. The risk models developed by the RAP form a categorical model based on the attributes and criteria identified. This section discusses how to score the models, and how to test the models to assess their effectiveness for prioritizing bridges for inspection based on risk.

A.5.1. Scoring Risk Models

The OF is calculated as a weighted sum model where the initial weights for the model were developed through an expert elicitation process with the RAP. The initial value weights for a given attribute were set by simply ranking the attribute as *high*, *moderate*, or *low* in terms of its impact on the reliability of bridge elements or components.

The criteria for each attribute are used to determine the actual score for the attribute when applied to a bridge component or element. Three criteria are typically developed to determine if the attribute should be rated *high*, *moderate*, and *low*. If an attribute is rated as *high* based on its criteria, the attribute is assigned 100% of its weight. If the attribute is rated as *moderate*, the attribute is assigned 50% of its weight, and if the attribute is rated as *low,* it is assigned 0 pts. Attribute can also be described by four levels of *very high*, *high*, *moderate*, and *low* with assigned point of 100%, 50%, 25% and 0%, respectively. Different point distributions can be used if needed to express the impact of the attribute based on expert judgement.

The rank of the attribute provides an initial weight for each attribute that determines the maximum number of points based on the RAP analysis. The OF factor score is determined by summing the rank and rating of each component in the model according to the equation:

$$OF = \sum w_i A_i \Big/ \sum w_i A_{i,\,max} \times 4$$

Where:

A_i = Original score for individual attribute based on its rating.
$A_{i,\,max}$ = Maximum score for an individual attribute.
w_i = Weighting factor assigned for a given attribute A_i.

Equation A-2. Weighted OF equation.

This equation uses the weights for each attribute according to the rank provided by the RAP ($A_{i,\,max}$) and the result of rating the attribute's criteria (A_i). The equation also allows for an attribute to have its weight modified using the weighting factor (w_i). For example, if an RAP initially ranked the attribute of CR as *high*, the attribute is assigned a maximum score of 20 points ($A_{i,\,max}$). A weighting factor (w_i) of 1.50 would increase the maximum score for the CR attribute to 30 points. If the CR attribute is rated *high* based on its criteria it would score 30 points. If the CR attribute is rated *moderate* it would score 15 points, while a rating of *low* scores zero points. The maximum score for the model, shown as the denominator in Equation

A-2, is also increased. In this way, increasing the weight of an individual attribute reduces the relative weight of all other attributes in the model, since the denominator is also increased.

The scores for each individual attribute are summed to produce the numerator and the maximum scores for each attribute are summed to form the denominator. The quotient is multiplied by 4 to place the OF on a scale of 1 to 4 to determine its location on the 4 x 4 risk matrix shown in Figure A.2(B).

Applying this scoring process to the risk model developed by the RAP provides an initial score. Since different RAPs may choose different attributes, different ranks for attributes, and different criteria for rating each attribute, the outcome produced from the model may or may not result in OF values that are consistent with expert judgement. For example, a risk model for a bridge deck could produce a risk score in the *high* range for the OF when the deck is in CR 8 and has many positive durability characteristics if the individual attributes are not weighted properly. To test and evaluate the potential outcome of the risk models developed by an RAP, target ranges can be used to test and refine the risk model results. The following section discusses target ranges established for this purpose.

A.5.2. Target Ranges for Risk Models

"Target ranges" based on engineering judgement and analysis of NBIS requirements can be used to evaluate models developed by the RAP to assess how the models would score typical bridges in each bridge inventory. Target ranges that can be used for analyzing the component models are as follows:

- Most components rated in CR 7 have risk scores in the *remote* range for the OF.
- Most components rated in CR 6 have risk scores in the *low* or *moderate* range for the OF, indicating increased risk as compared with CR 7 components and decreased risk as compared with CR 5 components.
- Components rated in CR 5 present increased risk as compared with components rated in CR 6 with many having risk scores in the *moderate* to *high* category for the OF.

Here "most" is considered as being more than 60% of CR 7 components. This is based on engineering judgement that most components in CR 7 have a very small likelihood of deteriorating rapidly to a serious condition (i.e., CR 3). These target ranges are not intended to be defined limits but rather target ranges to provide a means of weighting individual attributes.

A.5.3. Assessment of Risk Models

Attributes sometimes need to be weighted differently than estimated by the RAP to provide results that are consistent with the target ranges. For example, when there are few attributes in the risk model, one or two of the attributes being rated as *high* might result in *moderate* or *high* OF when engineering judgement suggests that a component should have a *remote* or *low* OF. A new bridge in good condition (CR ≥ 7) that has high Average Daily Traffic (ADT), or Average Daily Truck Traffic (ADTT), and has a CP level of only 2 might be rated as having a *low* or *moderate* OF, even though the likelihood of corrosion damage developing in the next 72 months might reasonably be judged as *remote.* Individual risk models can have a variety of different attributes and weights that need to be calibrated to be consistent with the target ranges and expert judgement.

Back-casting can be used to test the risk models by reviewing historical inspection records and applying the risk models to bridges based on past performance. Example bridges can also be used to analyze how the risk models would assess the risk for bridges in different conditions and with different attributes. More advanced modeling of the risk model outcomes can also be used. One effective approach in this research was the use of Monte Carlo (MC) simulations. Monte Carlo simulation is a common method of analyzing multi-variable processes when there is uncertainty in the variables that form the input. The method uses probabilistic theories to combine the results from different input variables and provide a variety of outputs that are *possible* outcomes given the probabilistic characteristics of the input. This approach can be used to assess the risk models by using existing bridge inventory data, combined with engineering estimates, to project or predict how the risk model would score a given inventory of bridges. The weights in the model (w_i) can then be adjusted to calibrate the risk model to produce results consistent with the target ranges.

A.6. Example Risk Model Scoring Analysis

This section presents an example of a Method 2 risk analysis for a bridge with a steel superstructure. The bridge family includes Stringer / Multi-beam or Girder steel bridges. The risk models developed by a RAP are presented first, followed by the CF analysis. Exemplary risk models from the RAP are shown to illustrate how the subject bridge is scored, and how the OF and Consequence Factor CF are combined to determine the appropriate inspection interval. Most items in the RAP models are determined from available bridge inventory and element-level inspection results. Items not available from existing data are identified as supplemental inspection data to be collected to obtain the data required by the criteria in the risk models. The risk models are presented in logical format amenable for computer programming.

Table A.10 shows partial list of data from the National Bridge Inventory (NBI) for the example bridge, showing the item number and code values for the bridge. The example bridge has five beam lines with 9 ft spacing.

Table A.10 Partial list of NBI items for the year 2020.

No.	NBI Item	Code Value
5C	Designated Level of Service	1
19	Bypass or Detour Length (mi.)	1.2
21	Maintenance Responsibility	1
27	Year Built	2004
28 A	Lanes on the Structure	2
28 B	Lanes Under the Structure	4
29	Average Daily Traffic (vpd)	9,000
42A	Type of Service On Bridge	1
42B	Type of Service Under Bridge	1
43A	Main Span Material	Steel Continuous
43B	Main Span Design	Stringer/Multi-beam or Girder
45	Number of Spans in Main Unit	2
46	Number of Approach Spans	0
48	Length of Maximum Span (ft)	145.3
49	Structure Length (ft)	310.7
54B	Minimum Vertical Underclearance (ft)	19.4
58	Deck Condition Rating	7
59	Superstructure Condition Rating	8
60	Substructure Condition Rating	9
61	Channel and Channel Protection Condition Rating	N
70	Bridge Posting Code	5
71	Waterway Adequacy Appraisal	N
107	Deck Structure Type Code	1
109	Average Daily Truck Traffic (Percent ADT)	9
113	Scour Critical Bridge Value	Bridge not over waterway

The element condition data for the example bridge are shown in Table A.11. The bridge elements include an R/C deck and a coated steel superstructure. The substructure consists of two R/C abutments and an R/C pier wall. The bridge is supported on movable bearings and the joints are strip seal expansion joints.

Table A.11. Listing of element condition states.

Component	Element No.	Element Name	CS 1 (%)	CS 2 (%)	CS 3 (%)	CS 4 (%)
Deck	12	R/C Deck	92	6	2	0
Superstructure	107	Steel Open Girder/Beam	90	10	0	0
Superstructure	515	Steel Protective Coating	85	12	3	0
Substructure	215	R/C Abutment	84	10	6	0
Substructure	205	R/C Pier Wall	95	5	0	0
Bearing	311	Movable Bearing	90	10	0	0
Joint	300	Strip Seal Expansion Joint	79	6	15	0

The results of the RAP meeting indicated there were five damage modes to be considered in the analysis as shown in Table A.12. The damage modes include delamination and spalling for the deck and concrete substructure, and corrosion damage / section loss, fatigue, and impact for the steel superstructure. Risk models were developed by the RAP for each of the damage modes. The following sections show the process of applying the risk model attributes and criteria to the bridge.

Table A.12. Listing of damage modes for steel bridges.

Component	Damage Mode
Deck	Deck Spalling/Delamination
Steel Superstructure	Corrosion / Section Loss
Steel Superstructure	Fatigue
Steel Superstructure	Impact
Concrete Substructure	Spalling / Delamination

A.6.1. Screening Criteria

The RAP identified 11 attributes as screening criteria for steel bridges as shown in Table A.13. The screening criteria include screening any bridge with components rated in CR ≤ 4 or CS 4 deck, superstructure, substructure or bearing elements, and bridges with low vertical clearance. The screening criteria also include bridges with active fatigue cracks due to primary stresses, bridges with fatigue category E or E' details, and details susceptible to constraint-induced fracture (CIF). Screening criteria for scour and waterway adequacy are included and are consistent with the Method 1 criteria for extended 48-month intervals. Screening criteria to screen substructures with moderate to severe rotation or settlement are also identified.

The bridge does not have reported settlement or rotation issues, and the substructure elements are reported to be in good condition. The LRF for the bridge is 1.1. There are no CS 4 elements on the bridge, and the bridge is not over water, so scouring is not an issue. The vertical clearance for the bridge is 19.4 ft. The bridge passes all the screening criteria.

A.6.2. Risk Model Scoring

The next step is to score the bridge for all the applicable risk models. The example bridge has five damage modes to be assessed. This section illustrates the scoring for each of the damage modes. The damage mode of Impact was addressed with a categorical model that does not require scoring. Each of these risk models are shown below.

Table A.13. Listing of screening criteria.

Code	Criteria
S.1	Current Condition Rating CR ≤ 4
S.3	Susceptible to Collision Vertical Clearance ≤ 14 ft
S.7	Active Fatigue Cracks Due to Primary Stress Ranges
S.8	Details Susceptible to Constraint Induced Fracture
S.10	Design Features Timber piles or timber pile bents Open grid steel or timber deck
S.13	E or E' Details
S.14	Scour Rating ≠ 5, 8, or N
S.15	Waterway Adequacy Channel Condition < 6
S.16	Current Element Condition State CS 4, Deck, superstructure, substructure, or bearing elements
S.19	Load Rating Factor < 1.0
S.20	Settlement or Rotation Moderate to severe rotation or settlement, or wide cracks resulting from rotation or settlement

A.6.2.1. R/C Deck, Spalling and Delamination Damage Mode

The attributes for deck delamination and spalling were scored as follows:

Condition Rating: The bridge deck is rated in CR 7. Rating = *low*, 0 points.

Element Condition State: The element-level inspection data indicates that there is 2% of the deck in CS 3. Rating **=** *moderate*, 10 points.

Efflorescence / Staining: Inspection reports do not indicate any efflorescence or rust staining. Rating = *low*, 0 points.

ADT: The NBI data lists the ADT as 9,000 vpd. Rating = *moderate*, 10 points.

Rate of De-icing Chemical Application: The bridge is north of I-70. Rating = *high*, 20 points.

Effectiveness of Deck Drainage System: The inspection report does not describe any drainage issues on the deck of the bridge. Rating = *low*, 0 points.

Corrosion Protection Level: The bridge was constructed in 2004 and does not have an overlay. Construction specifications required epoxy coated rebar (ECR) and 2.5 in. of concrete cover when the bridge was built. Therefore, there are two levels of corrosion protection. Rating = CP 2, 15 points.

Year of Construction: The bridge was constructed in 2004 and therefore is 20 years old. Rating = *moderate*, 7.5 points

Table A.14. Risk model for the R/C deck component.

Code	Attribute	Rank	Criteria	Total Points	Score
C.1	Condition Rating	High	CR 5 CR 6 **≥ CR 7**	20	0
C.2	Element Condition State	High	≥ 5% element in CS 3 **1% < CS 3 < 5%, CS 2 > 20%** CS3 ≤ 1%, CS2<=20%	20	10
C.13	Efflorescence / Staining	High	Efflorescence with rust staining Efflorescence without rust staining **No efflorescence**	20	0
L.1	ADT	High	ADT ≥ 15,000 vpd **7,500 ≤ ADT < 15,000 vpd** ADT < 7,500 vpd	20	10
L.5	Rate of De-icing Chemical Application	High	**I-70 and north of I-70, or urban area** NHS bridges south of I-70 South of I-70, non-urban, non-NHS	20	20
C.7	Effectiveness of Deck Drainage System	Mod.	Limited effectiveness Substantially effective **Fully effective**	15	0
D.26	Corrosion Protection Level	Very High	CP 1 **CP 2** CP 3 CP 4	30	15
D. 6	Year of Construction	Mod.	> 40 years **20 to 40 years** < 20 years	15	7.5
Total Points				160	**62.5**
OF rating / score				***Low***	**1.56**

The results show that the risk score for the deck is 1.56 resulting in the OF category of *low*.

A.6.2.2. Steel Superstructure, Corrosion/Section Loss Damage Mode

Current Condition Rating: The superstructure CR for this bridge is CR 8. Rating = *low*, 0 points.

Element Condition state: Element-level inspection results indicate the superstructure element is rated as CS 2 = 10% and CS 3 = 0%. Rating = *low*, 0 points.

Coating condition: Element-level inspection results indicate the coating is rated as CS 2 = 12% and CS 3 = 3%**.** Rating = *low*, 0 points.

Joint Condition: Element-level inspection results indicate the joints are rated as CS 2 = 6% and CS 3 = 15%.

Rating: *Moderate*, 10 pts.

ADT: The NBI data lists the ADT as 9,000 vpd. Rating = *Moderate*, 10 points.

Rate of deicing chemical application: The bridge is north of I-70. Rating = *Moderate*, 10 pts.

Subjected to overspray: This bridge has a minimum vertical clearance of 19.4 ft, and the feature below is an Interstate highway. Rating = *High,* 20 points.

Effectiveness of deck drainage system: Based on inspection results, there are no drainage issues on the bridge. Rating = *low*, 10 points.

Year of Construction: Bridge was constructed in 2004. Rating = *low*, 0 points.

Table A.15. Risk model for corrosion / section loss for steel superstructure.

Code	Attribute	Rank	Criteria	Total Points	Score
C.1	Current Condition Rating	High	CR 5 CR 6 **≥ CR 7**	20	0
C.2	Element Condition State	High	≥ 10% Element in CS 3 1% < CS 3 < 10%, CS 2 > 20% **CS 3 ≤ 1%**	20	0
C.17	Coating condition	High	EL 515 CS 3 ≥ 10%, CS 4 ≥ 1% CS 2 ≥ 30%, 5% ≤ CS 3 < 10%, **CS 2 < 30%, CS 3 < 5%**	20	0
C.4	Joint Condition	High	Leaking, CS 3 ≥ 25%, CS 4 ≥ 5% **5% < CS 3 < 25%, 1% ≤ CS 4 < 5%** Jointless or CS 3 ≤ 5%, CS 4 < 1%	20	10
L.1	ADT	High	ADT ≥ 15,000 vpd **7500 ≤ ADT < 15,000 vpd** ADT < 7,500	20	10
L.5	Rate of deicing chemical application	Mod.	**I-70 and north of I-70, or urban area** NHS bridges south of I-70 South of I-70, non-urban, non-NHS	15	15
L.6	Subjected to Overspray	High	**Over Interstate, < 20 ft vertical clearance** Over stream, < 6 ft vertical clearance Other	20	20
D.4	Poor Deck Drainage and Ponding	Mod.	Deck drainage onto superstructure. **Typical drainage**	15	0
D.6	Year of Construction	Mod.	> 40 years **20 to 40 years** < 20 years	15	7.5
Total Points				165	62.5
Risk Score and Ranking				***Low***	**1.52**

The results show that the risk score for the deck is 1.52 resulting in the OF category of *low*.

A.6.2.3. Steel Superstructure, Fatigue Cracking Damage Mode

Current Condition Rating: The superstructure CR for this bridge is CR 8. Rating = *low*, 0 points.

Current Element Condition State: Element-level inspection results indicate the superstructure element is rated as CS 2 = 10% and CS 3 = 0%. Rating = *low*, 0 points.

ADTT: The bridge has an ADT of 9,000 vpd with 9% truck traffic. Rating = *low*, 0 points.

Likelihood of overload: The bridge has an LRF of 1.1 and has a low likelihood of overload. Rating = *low*, 0 points.

Worst fatigue detail category: The worst fatigue detail category is determined to be category C based on a plan review. Rating = *moderate*, 0 points.

Year of Construction: The bridge was constructed in 2004. Rating = *low*, 0 points.

Table A.16. Risk model for fatigue cracking in steel superstructure.

Code	Attribute	Rank	Criteria	Total points	Score
C.1	Current Condition Rating	Mod.	CR 5 CR 6 **CR ≥ 7**	15	0
C.2	Current Element Condition State	Mod.	CS 3 > 5% 1% < CS 3 ≤ 5% **< 1% CS 3**	15	0
L.1	ADTT	High	≥ 5,000 ADTT 1,000 < ADTT < 5,000 **≤ 1,000 ADTT**	20	0
L.4	Likelihood of overload	Mod.	High Likelihood of overload Moderate Likelihood of overload **Low Likelihood of Overload**	15	0
D.17	Worst fatigue detail category	High	D **C** A, B, or B'	20	10
D.6	Year of Construction	High	Bridge designed before 1975/unknown Bridge designed between 1976 and 1984 Bridge designed between 1985 and 1993 **Bridge designed after 1994**	20	0
Total Points				105	10
Risk Score and Ranking				***Remote***	**0.38**

The resulting score for the risk model was 0.38, *remote*.

A.6.2.4. Steel Superstructure, Impact Damage Mode

The RAP assessed that the likelihood of impact damage depended on only two attributes, the vertical clearance and the ADTT on the roadway below the bridge. Because there were only two attributes to consider, the OF is determined from categories rather than from a scoring process. The bridge has a vertical clearance of 19.4 ft. As a result, the OF was determined to be *remote*.

Table A.17. Categorical model for impact damage mode.

Occurrence Factor	Criteria
High	Vertical clearance ≤ 14 ft., Screened
Moderate	14 ft < Vertical clearance < 16 ft ADTT ≥ 2,500 (feature under)
Low	14 ft ≤ Vertical clearance < 16 ft ADTT < 2,500 (feature under)
Remote	**Vertical clearance ≥ 16 ft**

A.6.2.5. Concrete Substructure - Spalling/Delamination Damage Mode

Current Condition Rating: The substructure CR for this bridge is CR 9. Rating = *low*, 0 points.

Current Element Condition State: Element-level inspection results indicate the substructure element of R/C abutment is rated as CS 2 = 10% and CS 3 = 6%. The substructure element of R/C pier wall is rated as CS 2 = 5% and CS 3 = 0%. Rating = *moderate*, 10 points.

Efflorescence / Staining: Inspection reports do not indicate any efflorescence or rust staining. Rating = *low*, 0 points.

Joint Condition: Element-level inspection results indicate the joint is rated as CS 2 = 6% and CS 3 = 15%.

Rating: *moderate*, 10 points.

Rate of deicing chemical application: The bridge is located north of I-70. Rating = *high*, 15 pts.

Feature Under: The feature under the bridge is a roadway. Rating = *low*, 0 points.

Corrosion Protection Level: The bridge was constructed in 2004 and does not have an overlay. Construction specifications required ECR and 2.5 in. of concrete cover when the bridge was built. Rating = CP 2, 15 points.

Table A.18. Risk model for delamination and spalling of substructure.

Code	Attribute	Rank	Criteria	Total Points	Score
C.1	Current Condition Rating	High	CR 5 CR 6 **≥ CR 7**	20	0
C.2	Current Element Condition State	High	CS 3 ≥ 10% **1% < CS 3 < 10%, CS 2 > 20%** CS 2 ≤ 20%, CS 3 ≤1%	20	10
C.13	Efflorescence /Staining	High	Efflorescence with rust staining Efflorescence without rust staining **No efflorescence**	20	0
C.4	Joint Condition	High	Leaking, CS 3 ≥ 25%, CS 4 ≥ 5% **5% < CS 3 < 25%, 1% ≤ CS 4 < 5%** Jointless or CS 3 ≤ 5%, CS 4 < 1	20	10
L.5	Rate of Deicing Chemical Application	Mod.	**I-70 and north of I-70, or urban area** NHS bridges south of I-70 South of I-70, non-urban, non-NHS	15	15
D.25	Feature Under	Mod.	Feature under is a waterway. Feature under is not a waterway.	15	0
D.26	Corrosion Protection Level	Very High	CP 1 **CP 2** CP 3 CP 4	30	15
Total Points				140	50
Risk Score and Ranking				***Low***	**1.43**

The resulting score for the risk model was 1.43, *low*.

Summary of OF Values: Table A.19 shows a summary of the OF values from the analysis of the risk models.

Table A.19. Summary of OF values from the analysis.

Component	Risk Score
Deck (Spalling and Delamination)	1.56
Superstructure (Steel-Corrosion)	1.52
Superstructure (Steel-Fatigue)	0.38
Superstructure (Impact)	*Remote*
Substructure (Concrete)	1.43

A.6.3. Consequence Factors

The next step is to determine the consequence factor for each of the damage modes. The attributes associated with the calculation of CF are described below. For the CF rating, the criteria described in Figure A.5 and Figure A.6 are applied to illustrate the process.

Redundancy: The multi-beam bridge has five beam lines with a beam spacing of 9 ft and is determined to be redundant. Therefore, the CF is *low*.

Load Capacity: Load Rating Factor (LRF) is 1.1. Therefore, the CF is *moderate*.

Safety: The feature under the bridge is a roadway with ADT of 11,000 vpd, which is less than the 75^{th} percentile for the ADT in the state. Therefore, the CF is *moderate*.

Serviceability: Traffic volume (ADT) on the bridge is in the range between the 25^{th} and 90^{th} percentile for the example state. Therefore, the CF is *moderate*.

The appropriate CF must be applied to each damage mode. Table A.20 shows damage modes and associated CFs. For the R/C deck damage mode of delamination and spalling, the CF associated with Safety and Serviceability were applied based on the scenarios of traffic disruption due to the damaged deck or debris falling into the roadway below. For the superstructure damage modes, three consequence scenarios were applied. Assuming the scenario that a member lost its load carrying capacity such that its loads needed to be transferred to adjacent members, the Redundancy and Load Capacity attributes were applied. A lane may need to be closed to divert loads from a damaged member, so the Serviceability attribute was applied.

Table A.20. Listing of the CF for the damage modes for the example bridge.

Component	Damage Mode	Applicable CF	Score
Deck	Deck Spalling/Delamination	Safety	*Moderate*
		Serviceability	*Moderate*
Steel Superstructure	Corrosion / Section Loss	Redundancy	*Low*
		Load Capacity	*Moderate*
		Serviceability	*Moderate*
	Fatigue	Redundancy	Low
		Load Capacity	*Moderate*
		Serviceability	*Moderate*
	Impact	Redundancy	Low
		Load Capacity	*Moderate*
		Serviceability	*Moderate*
Concrete Substructure	Spalling / Delamination	Serviceability	*Moderate*

A.6.4. Inspection Interval

Figure A.7 shows the risk matrix utilized to determine the inspection interval for each bridge component based on corresponding OF and CF values for each damage mode. Each OF category is paired with the appropriate CF for every damage mode. For example, the OF and CF values are 1.56 (*low*) and 2.0 (*moderate*), respectively, for the bridge deck. The location of each damage mode is shown on the risk matrix as A, B, C, D, and E (Table A.21). Therefore, referring to the risk matrix shown in Figure A.7, the inspection interval for the deck of this bridge was determined to be 72 months. The pairing of the OF and CF for each damage mode is shown in Table A.21.

In this case, all the CFs were rated as *moderate*. If the bridge carried very high ADT such that the CF was assessed to be rated *high*, the inspection interval would be determined to be 48 months instead of 72 months, based on placing the OF of *low* and the CF of *high* on the risk matrix shown in Figure A.7. These data are shown as A', B', C', D', and E'.

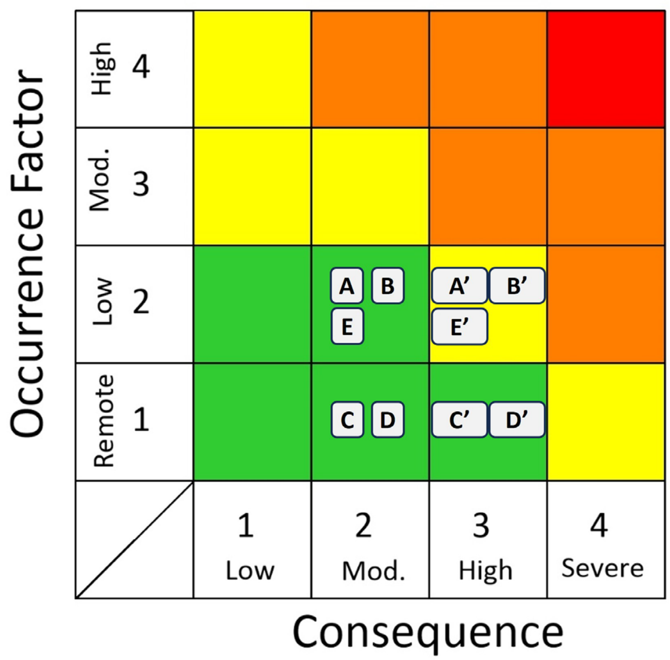


Figure A.7. Risk Matrix showing the results of the analysis.

Table A.21. Summary of the risk analysis showing the inspection intervals for each damage mode.

Component	Code	Damage Mode	OF	CF	Inspection Interval (months)
Deck	A	Deck Spalling/Delamination	*Low*	*Moderate*	72
Steel Superstructure	B	Corrosion / Section Loss	*Low*	*Moderate*	72
Steel Superstructure	C	Fatigue	*Low*	*Moderate*	72
Steel Superstructure	D	Impact	*Remote*	*Moderate*	72
Concrete Substructure	E	Spalling / Delamination	*Low*	*Moderate*	72

A.6.4.1. Additional Inspection Requirements

There are some attributes that are not available under standard element-level inspection procedures and would need to be collected to complete the risk models developed by the RAPs. Table A.22 lists additional inspection data that are needed to complete the models. These include having inspectors assess if there is moderate to severe settlement or rotation of substructure elements, if there is efflorescence, and an assessment of the drainage qualities on the bridge. For some agencies, this data may already be collected by Agency-Developed Elements or other inspection procedures.

Table A.22. List of additional inspection items for RBI.

Attribute Code	Attribute Description
S.20	Settlement or Rotation
C.13	Efflorescence / Staining
D.4	Poor Deck Drainage and Ponding
C.7	Effectiveness of Deck Drainage System

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