Synthesis of National and International Methodologies Used for Bridge Health Indices

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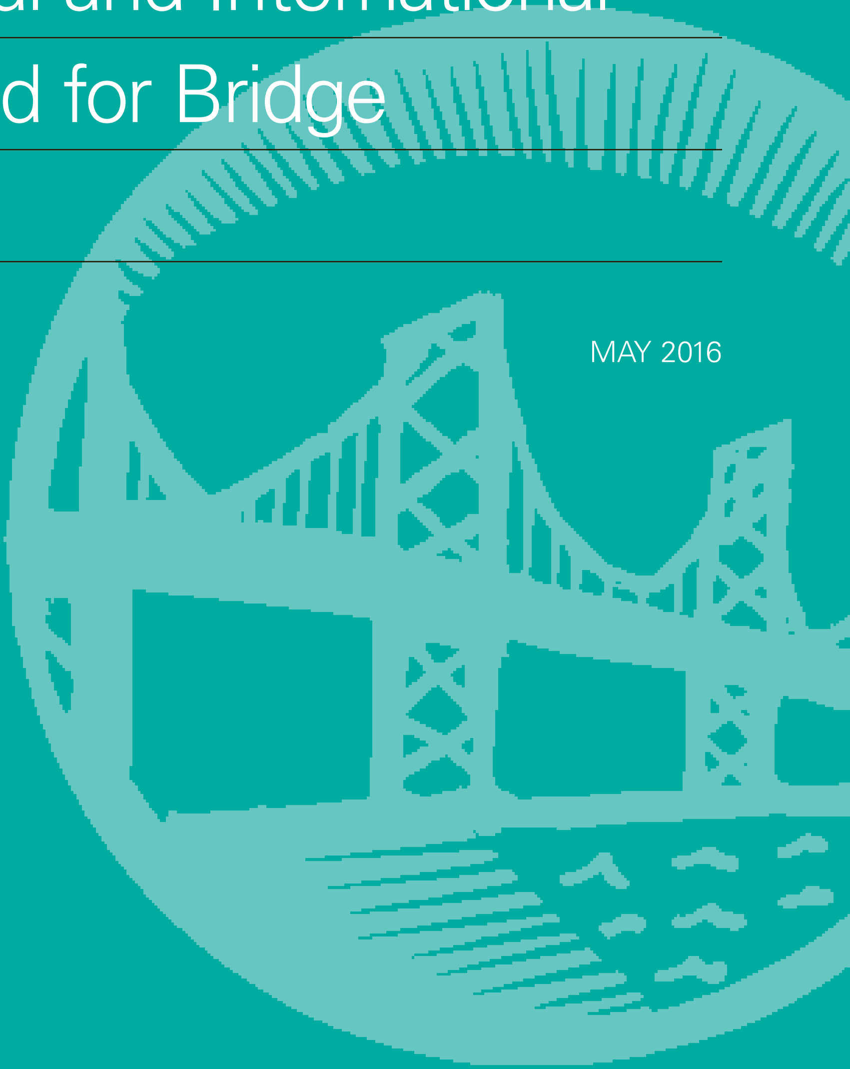

U.S. Department of Transportation
Federal Highway Administration

Long-Term
Bridge Performance
Program

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

This study was conducted as part of the Federal Highway Administration's Long-Term Bridge Performance (LTBP) Program. The LTBP Program is a long-term research effort, authorized by the U.S. Congress under *The Safe, Accountable, Flexible, Efficient Transportation Equity Act* legislation, to collect high-quality bridge data from a representative sample of highway bridges nationwide that will help the bridge community to better understand bridge performance. This report reviews the state-of-the-art with respect to bridge condition indices being used to assess performance of bridges in the United States and other countries. This report should be of interest to bridge program personnel from Federal, State, and local transportation departments as well as to parties engaged in bridge-related research.

Mark Swanlund
Acting Director, Office of Infrastructure
Research and Development

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16. Abstract

Bridge performance measures are important components of any successful Bridge Management System. Different types of performance measures have been developed for various purposes. The types of performance measures are usually a reflection of an agency's goals. The bridge health or condition index is a type of performance measure used by agencies interested in preserving the condition of bridge structures. Bridge condition index is very attractive because it provides a single index for assessment of the structural and or functional health of a bridge based on the condition of the bridge's structural elements and the services provided by the bridge. As outlined in the FHWA's Long-Term Bridge Performance Program, the development of condition indices should be driven by more objective and quantitative data to help bridge managers make informed decisions. This work reviews the state-of-the-art with respect to bridge condition indices being used to assess performance of bridges in the United States and other countries.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACR	average condition rating
ADT	average daily traffic
ADTT	average daily truck traffic
AGR	average group rating
BCFS	Bridge Condition Forecasting System
BCI	bridge condition index
BCN	bridge condition number
BCS	bridge condition score
BHI	bridge health index
BMS	bridge management system
BrM	AASHTOWare™ Bridge Management software
CEV	current element value
DER	degree, extent, and relevancy
ECF	element condition factor
ECS	element condition score
EIF	element importance factor
FC	failure cost
FHWA	Federal Highway Administration
Finnra	Finnish Road Administration
LTBP	Long-Term Bridge Performance
MAP-21	Moving Ahead for Progress in the 21st Century
NBI	National Bridge Inventory
NDE	nondestructive evaluation
NJDOT	New Jersey Department of Transportation
SR	sufficiency rating
TEQ	total element quantity
TEV	total element value
UBHI	universal bridge health index
VicRoads	Roads Corporation of Victoria
WF	weighting factor

CHAPTER 1. REVIEW OF METHODOLOGIES USED FOR BRIDGE HEALTH INDICES (BHIs)

INTRODUCTION

Bridge performance measures are an important component of any successful bridge management system (BMS). They can be used as a tool for communicating with legislatures, bridge managers, and, most importantly, the public on issues such as traffic safety and structural vulnerability of bridges to disasters such as earthquakes, scour, etc.(1,2) Different types of performance measures have been developed for various purposes. The type of performance measure is usually a reflection of the agency goals. A bridge health or condition index is used as a performance measure by agencies interested in preserving the condition of bridge structures or prioritizing the maintenance or replacement projects within their bridge inventory. Other performance measures, such as geometric and inventory ratings, are used to improve traffic safety of a bridge. Vulnerability and/or resiliency ratings are examples of performance measures used to show how vulnerable bridge structures are to structural or operational hazards such as hurricanes, earthquakes, or over-load trucks and how well they perform in these situations.

The bridge condition or health index is a useful tool for assessing the structural or functional health of a bridge. The index is calculated based on the condition of the bridge's structural elements and the service provided by the bridge. For the purposes of bridge management, the most important use of a BHI is to identify which structures in the inventory are the most deteriorated and are most urgently in need of repair work. Most BMSs also use a bridge condition index (BCI) to help track the general system condition over time, evaluate the benefits of an agency's bridge maintenance and rehabilitation programs, and serve as a basis for allocating resources to bridges within a network.

The increased availability of element-level inspection information influenced the redevelopment of BHIs used around the globe. Currently, most BMSs rely on element-level information for calculating BHIs.(2,3) Based on the computational approach used, current methods for developing condition or health indices can be grouped into the following four approaches:

- Ratio-based methods assign a BCI or bridge condition number (BCN) based on the ratio of the current condition to the condition of the structure when it was new. The objective for this method is to calculate the remaining value of the bridge. The California BHI and the health index method used by AASHTOWARE™ Bridge Management software, BrM (formerly Pontis),[1] are the examples for ratio-based methods discussed in this report.

- The weighted averaging approach is suitable for planning bridge maintenance and rehabilitation activities. The approach estimates the condition of the whole structure by combining condition ratings of all individual bridge elements weighted by their significance or contribution to the structural integrity of the bridge. This approach is

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[1] BrM is a BMS sold and maintained by the American Association of State Highway and Transportation Officials (AASHTO) and is widely used among State transportation departments in the United States.

common in systems that rely on element-level inspection data. BCIs used in Australia (BCN), the United Kingdom (BCI), South Africa (BCI), and Austria (BCI) are the examples of weighted combination approaches discussed in this report.

- The worst-conditioned component approach is common in systems that carry out inspections on key bridge components. This method is used to extract the critical defects in bridge components. In this approach, the BCI is approximated to the rating of the component in the worst condition. Some States also use the worst (lowest) National Bridge Inventory (NBI) rating to report bridge conditions at performance dashboards. The Michigan Department of Transportation uses the lowest NBI rating in its Bridge Condition Forecasting System (BCFS). BCFS helps Michigan with bridge project selection decisions. The German and Japanese BCIs are the examples of this approach and are discussed in this report.

- Qualitative methods do not report the condition of the bridge on a numerical scale. They describe a structure as either “Poor,” “Fair,” or “Good,” based on the condition state and importance of the elements under investigation. Washington, Florida, and other States use NBI condition ratings to classify bridges as “Good,” “Fair,” or “Poor.” The Bridge Health Indicator used by Roads and Maritime Services (merger of Roads and Traffic Authority and New South Wales Maritime) in Sydney, Australia, is discussed in this report as an example to highlight the use of qualitative methods in the assessment of overall bridge health.

There are other BHIs that were developed by combining some of the above listed methods. One example, no longer used in the United States, is sufficiency ratings (SRs), which combine the weighted averaging and the worst condition component approaches. The SR was used in funding decisions. Additionally, a risk-based prioritization method currently being tested by the New Jersey Department of Transportation (NJDOT) is also discussed in this report. This approach combines different performance limit states to calculate the perceived relative risk for each bridge.

Although resilience is a very important aspect for management of the bridge network, consensus metrics do not currently exist for it. Research programs are actively working on defining metrics and acceptable thresholds to address bridge resilience aspects. Some examples of possible resilience metrics include the following:

- Regional conditions such as natural hazard zones.

- Geology, seismicity, and geotechnical features of the site (e.g., faulting, landslides, or liquefaction).

- Toughness and resilience in the event of damage or element failure (e.g., loss of a girder or fatigue-induced fracture not leading to collapse).

Although some of these metrics do not currently exist, they may be quantifiable through expert elicitation and risk assessment.

This report reviews state-of-the-art BCIs being used as one metric to assess performance of bridges in the United States and other countries. Table 1 summarizes these indices and their calculation approaches.

Table 1. Summary of BHIs and their calculation approaches.

Index Name	Calculation Approach
California BHI	Ratio based
United Kingdom's BCI	Weighted average
South Africa's BCI	Weighted average
Australia's BCN	Weighted average
Austria's BCI	Weighted average
Finnish Bridge Condition Rating	Weighted average
Germany's BCI	Worst conditioned component
Japan's BCI	Worst conditioned component
Australia's Bridge Health Indicator	Qualitative method
Austria's Qualitative Bridge Rating	Qualitative method
Bridge Sufficiency Rating	Formulaic combination of many parameters
Risk-Based Assessment Framework	Formulaic combination of risk scores

To facilitate comparison between different bridge condition or health indices, each system is reviewed based on the following:

- **Computational Approach**—The general approach used in calculating the health index (e.g., ratio-based, weighted average, worst conditioned component, qualitative, or other approach).
- **Data Inventory and Condition Rating**—Relevant data input for computing the condition index (e.g., types of damage observed, severity of damage, extent of damage, urgency of damage, etc.).
- **Condition Index**—Steps used to aggregate the condition information and calculate the overall BHI.
- **Strengths and Limitations**—Discussion of the key strengths and limitations of the health index.

CHAPTER 2. RATIO-BASED CONDITION INDEX

COMPUTATIONAL APPROACH OVERVIEW

A ratio-based condition index is frequently used in the United States, Canada, Italy, Japan, and other parts of the world.(4–6) It assigns a condition index based on the ratio of the current condition to the condition of structure when it was new.

These indices are mostly adapted from the California BHI, which is a concept originally developed by the California Department of Transportation to generate a single-number measure of the structural performance of a bridge or a network of bridges. The index assesses the current condition of a bridge by aggregating the current condition value of all the elements of the bridge and comparing it to the total value of the bridge elements when they were in their best possible state. The value of each element is proportional to the quantity of elements in the present condition and the economic consequence of the element's failure. The element's failure cost (FC) can be seen as a weight emphasizing the importance of the element to the overall health of the bridge.

DATA INVENTORY AND CONDITION RATINGS

The development of most ratio-based condition indices is based on the following two primary sources of data:

- Element-level bridge condition data.
- Element failure or replacement cost data.

Element-Level Condition Data

Element-level inspections capture the conditions of more detailed components compared with the NBI database used by the Federal Highway Administration (FHWA). For instance, instead of rating the condition of the whole superstructure (NBI case), an element-level inspection looks at the condition of the individual components of the superstructure, such as girders, floor beams, pins, hangers, bearings, etc.

Inspectors rate the condition of elements according to the following states and descriptions: "Good" (1), "Fair" (2), "Poor" (3), and "Severe" (4). The number of states and descriptions used was standardized by the AASHTO *Manual for Bridge Element Inspection*, which was published and adopted in 2013.(7)

One of the key strengths of element-level inspection is its ability to simultaneously capture the severity and extent of deterioration of an element. For example, an inspection of a girder reports the percentage, or extent, of the girder that is in the different condition states (e.g., 10 percent in condition 1, 25 percent in condition 2, and 65 percent in condition 3).

Element Failure or Replacement Cost Data

The cost associated with the failure of an element is estimated from one of the following two main sources:

- **Agency and User Cost Estimates**—The cost to the agency may include operating costs, cost of inspection, cost of maintenance, rehabilitation, etc. Examples of user costs include estimated costs associated with delays when traffic flow is restricted or diverted, increases in vehicle operating costs due to bridge inadequacies, upkeep of detours, etc. Also, note that the costs are only for one element. The current BHI method does not consider the effect of subordinate elements.
- **Element Replacement Cost**—This cost is estimated by expert bridge engineers.

Calculating the California BHI

BHI is based on the premise that a bridge has an initial asset value when it is commissioned. This value depreciates due to deterioration caused by traffic loading and environmental effects. Interventions through maintenance or rehabilitation improves the value and corresponding condition of the bridge asset.(4) The BHI is calculated as the ratio of the aggregate remaining value of the bridge elements to the total initial value of the element. The following steps are used to calculate BHI.

Step 1

Obtain element-level inspection data from BrM (table 2), with the understanding that an element can have portions of it in more than one condition state.

Table 2. Sample element-level inspection data.

Element	Unit	Total Element Quantity	State 1 Q_1	State 2 Q_2	State 3 Q_3	State 4 Q_4	State 5 Q_5	Element FC
Steel girder	m	100	40	30	30	0	0	$9,600
Column	ea	4	0	0	4	0	0	$7,500

Q_n = Quantity of each element in each condition state.
n = Number of condition state for each element.
ea = Each.

Step 2

Calculate a weighting factor (WF) for each of the condition states (figure 1). Table 3 shows an example of WFs for various number of condition states.

$$\text{WF} = \frac{\text{Condition State Number} - 1}{\text{Number of Condition States} - 1}$$

Figure 1. Equation. Condition state WF.

Table 3. WFs for each condition state.

Number of Condition States	Condition State 1 WF	Condition State 2 WF	Condition State 3 WF	Condition State 4 WF
4	1	0.67	0.33	0

Step 3

Based on current element conditions in step 1, estimate the FC of each element (table 2). The two approaches for calculating FC are as follows:

- Element agency FC plus element user FC.
- Element replacement cost multiplied by element WF.

These cost values are established through expert solicitation.

Step 4

Calculate the total element value (TEV) (figure 2) and the current element value (CEV) (figure 3).

$$TEV = TEQ * FC$$

Figure 2. Equation. TEV.

$$CEV = \sum (Q_i * WF_i) * FC$$

Figure 3. Equation. CEV.

Step 5

Calculate the BHI as the ratio of the TEV to the CEV (figure 4).

$$BHI = \frac{\sum CEV}{\sum TEV} * 100$$

Figure 4. Equation. BHI.

STRENGTHS AND LIMITATIONS

Strengths

The use of element-level inspection data provides a thorough and objective assessment of the condition of the bridge. Inspectors are able to capture both the severity and extent of any problems that may influence the integrity of the structure. Such information is valuable for planning maintenance, repair, and rehabilitation programs.

The health index is also useful for structural health comparisons and resource allocation for a network of bridges. Some State agencies are mostly interested in fixing bridges with the most severe deficiencies rather than those with clearance and geometric (functional) issues. In such cases, the health index can be incorporated into prioritization models used for allocating funds for the repair and rehabilitation of bridges with a low health index.

Limitations

Availability of Element-Level Data

Many agencies, especially at the county level, do not collect element-level data required for computing the health index. The recently adopted AASHTO *Manual for Bridge Element Inspection* provides standard guidelines for assessing how good or poor the bridge condition is, resulting in a more uniform basis for the computed health index.(7)

FC Data

In estimating the FC of an element, since the true cost of an element's failure is unknown, several assumptions and estimations have to be made. This makes the FC uncertain. FCs are sometimes related to agency and user costs, which are very difficult to estimate. Different agencies will have different FCs. Anything outside the true FC is an estimate and therefore uncertain. The variability of FC estimates also increases the difficulty of standardizing the BHI across agencies and countries. A replacement cost of one element varies from State to State and project to project. Since the replacement cost varies, the health index also becomes variable and uncertain. Equal health indices from two different regions might not necessarily mean that the two bridges have similar structural condition. Relative structural health comparisons between bridges is therefore challenging.

The Universal Bridge Health Index (UBHI), developed by Sivakumar et al., was intended to standardize the use of the index across different States and countries.(9) The UBHI does not consider economic value of elements; rather, their physical conditions are used. This helps reduce the uncertainties associated with estimating the significance of bridge elements. In place of the economic worth or FCs, the UBHI calculates a structural significance factor and material vulnerability factor. These two factors, although less uncertain compared with economic cost, are still very subjective. The structure significance is found by comparing the role of one element to the role of other elements with a range of 1 (least significant) to 4 (most significant).

Computational Issues

In calculating the health index, only conditions of structural elements of the bridge are considered. The bridge's functional adequacies (service provided by the bridge) such as capacity, traffic volume, and clearance issues are ignored. Corporate bridge risk factors such as scour, seismic, and fatigue are also not incorporated. Therefore, although the health index provides management with an indicator of the overall condition of the bridge, it is not a complete measure of the value of the agency's investments.

CHAPTER 3. WEIGHTED AVERAGE APPROACHES

COMPUTATIONAL APPROACH OVERVIEW

BCIs calculated by weighted averaging of individual element conditions are the most common types identified in this report. Their development is based on structural element condition data, which captures the type, severity, and extent of deteriorations. Also, some indices rely on operational data such as traffic volume to capture the service provided by the bridge. The number of elements inspected and the type of rating systems adopted may be different from one country to the other.

UNITED KINGDOM'S BCI

Just like the California BHI, the United Kingdom's BCI describes the condition of an element based on its condition state and the extent of deterioration. The key difference is that the value of the bridge elements' conditions is based on its contribution to the overall bridge integrity and not the cost of the elements' failure. Instead of calculating the remaining value of the bridge elements, a simple score based on engineering judgment is used to assign importance factors to each element. Also, the extent of damage is registered in qualitative terms. Table 4 and table 5 provide a description for different categories of damage severity and extent used for calculating the United Kingdom's BCI.

Table 4. Extent descriptions.(10)

Extent	Description
A	No significant defect.
B	Slight (not more than 5 percent of surface area or length).
C	Moderate (5 to 20 percent of surface area or length).
D	Wide (20 to 50 percent of surface area or length
E	Extensive (more than 50 percent of surface area or length)

Table 5. Severity descriptions.(10)

Severity	Description
1	As-new condition or defect has no significant effect on the element (visually or functionally).
2	Early signs of deterioration; minor defect; no reduction in functionality of element.
3	Moderate defect/damage; some loss of functionality could be expected.
4	Severe defect/damage; significant loss of functionality and/or element is close to failure.
5	The element is non-functional/failed.

Calculating British BCI

The BCI is calculated as follows.(11)

Step 1

Assign an element condition score (ECS) for each element based on its severity and extent of deterioration (table 6). For example, an element with a severity of 3 and an extent of C receives a score of 3.2. In this approach, higher scores suggest worse conditions.

Table 6. ECS.(10)

	Severity				
Extent	**1**	**2**	**3**	**4**	**5**
A	1.0	*	*	*	*
B	1.0	2.0	3.0	4.0	5.0
C	1.1	2.1	3.2	4.1	
D	1.3	2.3	3.3	4.3	
E	1.7	2.7	3.7	4.7	

*Non-permissible severity-extent combinations.

Step 2

Assign an element importance factor (EIF) for each element. EIF accounts for the value of the element (table 7).

Table 7. EIF.(10)

Element Importance	**EIF Value**
Very high	2.0
High	1.5
Medium	1.2
Low	1.0

Step 3

Assign an element condition factor (ECF). ECF accounts for an element's contribution to the overall bridge condition. Therefore, ECF of an element is calculated with respect to its importance (figure 5 through figure 7); an element with an importance of "very high" has an ECF of 0.(10)

$$ECF_H = 0.3 - [(ECS - 1) * \frac{0.3}{4}]$$

Figure 5. Equation. ECF ("high" element importance).(10)

$$ECF_M = 0.6 - [(ECS - 1) * \frac{0.6}{4}]$$

Figure 6. Equation. ECF ("medium" element importance).(10)

$$ECF_L = 1.2 - [(ECS - 1) * \frac{1.2}{4}]$$

Figure 7. Equation. ECF ("low" element importance).(10)

Step 4

Calculate the element condition index (ECI) (figure 8).

$$ECI = ECS - ECF$$

Figure 8. Equation. ECI.

Step 5

Calculate the overall bridge condition score (BCS). BCS is calculated by a weighted combination of all the contributions of each bridge element. The weights are assigned based on the element's importance (figure 9).

$$BCS = \frac{\sum_{i=1}^{N} (ECI_i * EIF_i)}{\sum_{i=1}^{N} EIF_i}$$

Figure 9. Equation. BCS.

Where:

N = Total number of bridge elements for structure.

Step 6

Calculate the BCI (figure 10). The condition of the bridge is based on the BCI value on a scale of 0 (worst) to 100 (best) (table 8).

$$BCI = 100 - (2 * \{(BCS)^2 + (6.5 * BCS) - 7.5\})$$

Figure 10. Equation. BCI.

Table 8. BCI condition.

BCI Value	Condition
90 ≤ BCI ≤ 100	Very good
80 ≤ BCI < 90	Good
65 ≤ BCI < 80	Fair
40 ≤ BCI < 65	Poor
0 ≤ BCI < 40	Very poor

SOUTH AFRICA'S BCI

The South African BMS allocates funds and prioritizes maintenance, repair, and rehabilitation needs by using an index similar to the British BCI. The BCI is calculated based on data obtained from routine structural condition assessments and a bridge importance factor, which is based on the average daily traffic (ADT) of the bridge.

Condition Ratings

Condition assessment of structures is performed based on the degree, extent, and relevancy (DER) of deterioration by assigning a DER score. The DER rating system identifies defects and prioritizes them by evaluating their relative importance to the structural integrity of the bridge.(12) It is important to note that the ratings are not directly associated with the elements but with the distress or damage. Thus, with the DER rating system, an element is assigned a score greater than zero only if it has a distress on it.

Each distress identified is assigned a rating from 1 (minor) to 4 (severe) depending on the degree (how severe is the defect), extent (how widespread is the defect on the inspected element), and relevancy of the damage. The relevancy of the identified damage corresponds to the general impact of the defect with regards to structural integrity, serviceability, and safety of the bridge. Two defects may look the same and have the same extent, but their impact on the integrity of a bridge from a global point of view can be different. Therefore, the relevancy of the distress helps the inspectors capture information beyond ordinary visual ratings by assessing the impact of each distress on the overall structural integrity of the bridge.(13) The DER rating system is summarized in table 9. An urgency category is also assigned based on the DER value, but it is not used to determine the BCI.

Table 9. DER rating values.(12)

	Degree	Extent	Relevancy	Urgency
0	None	N/A	N/A	Monitor only
1	Minor	Local	Minimum	Routine
2	Fair	> Local	Moderate	< 5 years
3	Poor	< General	Major	< 2 years
4	Severe	General	Critical	As soon as possible

N/A = Not applicable.

Calculating South African BCI

Each defect on the element being inspected has a condition index (I_{Cj}) (figure 11).(12)

$$I_{Cj} = 100 * \left[1 - \frac{(D+E)*R}{32}\right]$$

Figure 11. Equation. Defect condition index.

Where:

D = Degree of damage.
E = Extent of damage.

R = Relevancy of damage.

The bridge importance (figure 12) is based on how frequently the bridge is used or traveled in the network. Therefore, the overall BCI (figure 13) is computed as the sum of all defect condition values for all elements inspected weighted by a bridge importance factor.

$$Bridge\ Importance = \frac{ADT_i}{\sum_{i=1}^{n} ADT_i}$$

Figure 12. Equation. Bridge importance factor.

Where:

ADT_i = ADT for structure i.
n = Number of bridges in the network being evaluated.

$$BCI_i = \frac{\left(\sum_{j=1}^{m} Ic_j\right) * ADT_i}{\sum_{i=1}^{n} ADT_i}$$

Figure 13. Equation. Final bridge condition.

Where:

BCI_i = BCI for structure i.
m = Number of inspected elements on structure i.
j = Individual element on structure i.

AUSTRALIA'S BCN

Roads Corporation of Victoria (VicRoads), the roadway agency for Victoria, Australia, uses a BCN for relative comparison of the performance, integrity, and durability of bridge structures.(14)

Calculating Australian BCN

BCN is calculated based on a three-level hierarchical framework (figure 14). The first level (element level) calculates element-level condition ratings by aggregating condition state percentages for each element. At the second level (group level), structural group factors are assigned based on the group's importance to the structure. A structural group consists of a number of elements which perform similar functions (e.g., bearings, piers, decks, etc.).

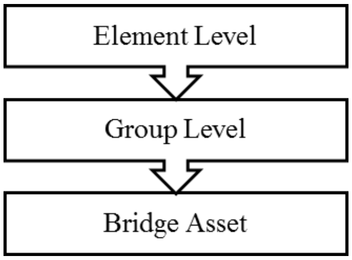

Figure 14. Illustration. Three-level hierarchy for calculating Australian BCN.

It is important to note that the level of importance is assigned at the structural group level and not at the element level. Combining all the average structural group ratings yields the overall BCN.

Element Level

Calculate the average condition rating (ACR) for each element (figure 15). Condition state numbers are subjective scores represtative of element condition, ranging from 1 to 4, with 1 being as-built and 4 being poor. Explicit definitions are provided in Rummey and Downling.(14) Only critical elements are considered in this step.

$$ACR = \frac{\sum Condition\ State\ No. \times\ condition\ \%}{100}$$

Figure 15. Equation. ACR for each element.

Group Level (Piers, Decks, Bearings)

Calculate the average group rating (AGR) for each structural groups or categories (figure 16).

$$AGR = \frac{\sum[2 \times ACR + E^{0.5}]}{No. of\ Elements}$$

Figure 16. Equation. AGR for each structural group/category.

Where:

E = Exposure factor (environment).

Bridge Asset

BCN is calculated in this step (figure 17) using the AGR for bridge element groups.

$$BCN = \sum [AGR \times W_b]$$

Figure 17. Equation. BCN.

Where:

W_b = Structural group importance.

Table 10 shows how VicRoads uses the BCN for decisionmaking and prioritization.

Table 10. Decisionmaking with BCN.

BCN	Interpretation	Inspection Interval (years)
BCN < 30	Free from defects affecting performance and durability.	5
30 < BCN < 60	Structure has defect affecting durability.	3
BCN > 60	Structure has defects affecting both performance and structural integrity or durability.	2

AUSTRIA'S BCI

Austria's BCI is calculated using inspection data from bridge elements. Each element is assigned five different ratings based on the following attributes:(15)

- **Type of Damage**—Rated between 1 and 5 for each of 32 types of damage that can be identified.
- **Extent of Damage**—Rated between 0 and 1. The extent is not quantified in measured size of defects (e.g., length or area).
- **Severity or Intensity of Damage**—Rated between 0 and 1.
- **Importance of the Structural Components**—Rated between 0 and 1 and classified as primary, secondary, and other parts.
- **Urgency of Intervention**—Rated between 0 and 10 and is dependent on the risk of collapse of the structure or element. This attribute is not used in calculating the index.

Calculating Austrian BCI

The overall bridge condition rating (S) is calculated by weighting the type of distress by the square root of the sum of all the above mentioned attributes (figure 18).

$$S = \sum_{I=1}^{32} G_i * \sqrt{k_{1i} + k_{2i} + k_{3i}}$$

Figure 18. Equation. Overall bridge condition rating.

Where:

G_i = Type of damage to element i.
k_{1i} = Extent of damage to element i.
k_{2i} = Severity of damage to element i.
k_{3i} = Importance of component to element i.

FINLAND'S BCI

The BMS used by the Finnish Road Administration (Finnra) uses a condition index based on weighted averaging of condition ratings of structural parts.(12) The weights, assigned by structural part, are presented in table 11. Examples of inputs used to calculate the BCI includes damage cause, damage location, damage effect on bridge load capacity, and urgency of repair.

Calculating Finnish BCI

BCI, also known as the repair index, is computed for the set of identified defects on the bridge (see table 12). The bridge is divided into nine structural parts during inspection. The condition of each structural part is evaluated on a rating from 0 (very good) to 4 (very poor). Each instance of damage detected during inspection is also rated in terms of its severity and urgency of repair. Values for these ratings are shown in table 13 and table 14.

Table 11. Structural component weights.

Bridge Structural Part	Weight
Substructure	0.70
Edge beam	0.20
Superstructure	1.00
Overlay	0.30
Other surface structure	0.50
Railings	0.40
Expansion joints	0.20
Other	0.30
Bridge site	0.30

Table 12. Condition ratings.

Condition Rating	Condition Points
0—New	1
1—Good	2
2—Satisfactory	4
3—Poor	7
4—Very Poor	11

Table 13. Repair urgency.

Repair Class	Repair Urgency Points
11—Repair during the next 2 years	10
12—Repair during the next 4 years	5
13—Repair in the future	1

Table 14. Damage severity.

Damage Class	Damage Severity Points
1—Mild	1
2—Moderate	2
3—Serious	4
4—Very Serious	7

The repair index is computed for all identified defects (figure 19). The equation maximizes the worst defects and minimizes all other defects by a factor k, which has a default value of 0.2.

$$KTI = \max(Wt_i * C_i * U_i * D_i) + k \sum (Wt_j * C_j * U_j * D_j)$$

Figure 19. Equation. Repair index.

Where:

KTI = Repair index.
Wt = Weight assigned to structural part.
i = Index representing the worst defect on a given structural part.
C = Condition of structural part.
U = Urgency of the repair needed for structural part.
D = Severity of damage to structural part.
k = WF for other defects apart from the worst defect.
j = Indices representing the rest of the defects on a given structural part.

STRENGTHS AND LIMITATIONS

Strengths

The weighted averaging condition indices capture the degree, severity, and importance of every instance of damage identified during the inspection process, which helps provide a comprehensive picture of the condition of the bridge. Also, the approach is suitable for planning for bridge maintenance and rehabilitation activities because the overall index combines all defects identified at the element level. These indices provide a consistent framework within an agency, and engineering judgment has been incorporated by assigning categories rather than rigid numerical scores.

Limitations

The health index only captures conditions of structural elements of the bridge. Although the bridge's functional adequacies (service provided by the bridge) such as capacity, traffic volume, and clearance issues are considered during maintenance prioritization and fund allocation, there is no index in the weighted average category integrating both structural condition and functional information. Finnra overcomes this challenge by using a rehabilitation index that combines structural condition information with some functional information.(12)

With the exception of the Australian BCN and Finnra's repair index, most of the weighted combination health indices assign weights (significance level) at the element level. This is challenging because it is very difficult to assess the impact of the condition of an element on the overall bridge structure. Estimating the importance of a structural group (consisting of a number of elements with similar primary functions) is more practical.

CHAPTER 4. WORST-CONDITIONED COMPONENT APPROACHES

COMPUTATIONAL APPROACH OVERVIEW

The worst-conditioned approach is driven by bridge component condition data that capture the severity and extent of identified forms of deterioration. The approach captures information about the critical defects in bridge components. Not all damage is factored into the calculation of overall BCI. The condition rating of the whole structure corresponds to the state of the worst conditioned components. The component in the worst condition is related to the individual damage with the worst rating based on its severity and frequency of occurrence among other components of the structure. The number of components contributing to the index and the type of rating system adopted may be different from one country to the other.

GERMANY'S BCI

The German BCI uses a hierarchical approach to assess the overall health of a structure. At the lowest level, an index is assigned to each individual damage identified. The next level involves calculating a condition index for predefined groups of structural components (i.e., piers, bearings, etc.) followed by a final level that computes the overall BCI.

Each instance of damage detected during inspection is rated on a five-level scale in terms of its effect on the bridge's structural stability (table 15), traffic safety (table 16), and the bridge's durability (table 17). The extent of damage is not quantified by measured length or area. It is described qualitatively as either small, medium, or large. From this information, a decimal condition index (table 18) ranging from 1.0 (very good condition) to 4.0 (insufficient condition) is assigned for each damage.

Table 15. Damage ratings for structural stability.[3]

Assessment	Description
0	Defects have no effect on structural stability of elements or overall structure.
1	Defects affect stability of structure elements but not the overall structure.
2	Defects affect stability of structure elements and have little effect on stability of overall structure.
3	The effect of defects on stability of structural elements and the overall structure is beyond permissible tolerance.
4	The structural stability of structural elements and the structure itself no longer exists.

Table 16. Damage ratings for traffic safety.(3)

Assessment	Description
0	Defects have no effect on traffic safety.
1	Defects affect traffic safety only slightly.
2	Defects may impair traffic safety.
3	Defects affect traffic safety.
4	Traffic safety is no longer given due to defects.

Table 17. Damage ratings for durability.(3)

Assessment	Description
0	Defects have no effect on durability.
1	Defects affect durability of structure elements but not the durability of the overall structure.
2	Defects affect durability of the structure elements and, in the long term, can affect the overall structure.
3	Defects affect durability of the structure elements and, in the medium term, can affect the overall structure.
4	The durability of both the structure element and the overall structure is no longer given due to the defects.

Table 18. Damage condition ratings.[3]

Condition Rating	Description
1.0–1.4	• Very good structural condition. • The stability, traffic safety, and durability of the structure is assured.
1.5–1.9	• Good structure condition. • Stability and safety of structure is assured. • Durability might be impaired slightly in the long term.
2.0–2.4	• Temporarily satisfactory structural condition. • Stability and safety of structure is assured. • The durability of the structure might be impaired considerably in the long term.
2.5–2.9	• Unsatisfactory structural condition. • Stability of structure is assured. • Traffic safety can be impaired. • The durability of the structure might be impaired considerably in the long term.
3.0–3.4	• Critical structural condition. • Traffic safety is affected. • Structure is not durable. • Immediate repair is needed.
3.5–4.0	• Inadequate structural condition. • Traffic safety is not adequate. • Structure is not durable. • Immediate repair or rehabilitation is needed.

Calculating German BCI

The overall condition of the bridge corresponds to the rating of the worst component rather than the aggregate component conditions.

Damage Index

Each component is surveyed for damage or deterioration. For each individual occurrence of damage, an index (Z_i) is calculated based on its effect on traffic safety, stability, and durability. The condition index is supplemented with the extent of the identified damage (Δ_1) and assigned a value (table 19).

Table 19. Identified damage values.

Δ_1 Value	Damage Extent
-0.1	Small
0.0	Medium
+0.1	Large

Each component group (CG) consists of damage ratings for each individual occurrence (figure 20).

$$CG = \{Z_1, Z_2, Z_{3,\ldots\ldots,}Z_N\}$$

Figure 20. Equation. Component group.

Next, a component group condition index is calculated.

Component Group-Level Condition Index

The index at the component group level is equivalent to the maximum ratings assigned to damage at the subcomponent level. The number of occurrences of the damage identified within the component group (Δ_2) is accounted for in calculating the component group condition index (Z_{CG_i}) (figure 21).

$$Z_{CG\_1} = \max\{Z_i\} + \Delta_2$$

Figure 21. Equation. Component group condition index.

For a substructure component group, Δ_2 is assigned a value according to table 20.

Table 20. Values of Δ_2 for substructure component groups.

Δ_2 Value	Number of Damage Occurrences (n)
-0.1	$n < 5$
0.0	$5 \leq n \geq 15$
+0.1	$n > 15$

For all other components groups, Δ_2 is assigned a value according to table 21.

Table 21. Values of Δ_2 or other component groups.

Δ_2 Value	Number of Damage Occurrences
-0.1	$n < 3$
0.0	$3 \leq n \geq 5$
+0.1	$n > 5$

Structure-Level Index

The overall bridge condition index (Z_{ges}) (figure 22) corresponds to the maximum rating at the component group level, taking into consideration the extent of damage to other component groups. The extent of damage to other component groups (Δ_3) is assigned a value based on the number of damaged component groups (table 22).

$$Z_{ges} = \max\{Z_{CG}\} + \Delta_3$$

Figure 22. Equation. German BCI.

Table 22. Values of Δ_3.

Δ_3 Value	Number of Damaged Component Groups
-0.1	1 to 3
0.0	4 to 5
+0.1	more than 5

JAPAN'S BCI

The Japan BMS uses visual inspection to assess the condition of bridge components at the element level.(16) Each instance of damage is described based on the type and severity of deterioration alone. A deficiency (or condition) rating is established for each identified instance of damage. During inspection, each element is divided into units, and the condition of the structure is assessed by aggregation of units.

Japan's BCI is slightly different from that of Germany. It calculates the overall BCI by aggregating worst defects (in terms of severity) detected for all components, whereas the German BCI selects the worst component as the condition of the overall bridge, with no aggregation required. Also, Japan's BCI calculation does not directly incorporate the extent of damage.

Calculating Japanese BCI

Step 1

Assign deficiency ratings (table 23) for each defect within each structural component of the bridge.

Table 23. List of deficiency ratings.(16)

Deficiency Rating	Description
I	Serious damage. There is a possibility of danger to traffic.
II	Damage in a large area. Detailed investigation is required.
III	Damage. Follow-up investigation is required.
IV	Slight damage. Inspection data are recorded.
OK	No damage.

Step 2

Calculate a demerit rating (d) corresponding to the deficiency rating for each type of defect (figure 23). Demerit rating for distress with worst deficiency ratings (d_I) is assigned and not calculated. The remaining demerit ratings are calculated as follows:

$$d_{II} = d_I * \propto_{II}$$
$$d_{III} = d_{II} * \propto_{III}$$
$$d_{IV} = d_{III} * \propto_{IV}$$
$$d_{OK} = 0$$

Figure 23. Equation. Demerit ratings.

Where:

$\propto$ = Reducing ratio (table 24) corresponding to each deficiency rating.

Table 24. Deficiency ratings and reducing ratios.(16)

Deficiency Rating	Reducing Ratio
I	1
II	0.5
III	0.2
IV	0.05
OK	0

Step 3

Determine the value of the demerit rating for each structural component by taking the maximum demerit rating for all defects with that component group.

Step 4

Calculate the overall bridge condition rating by adding all defective ratings for the structural groups and subtracting it from 100.

STRENGTHS AND LIMITATIONS

Strengths

Worst-conditioned component approaches are useful for assessing the vulnerability of a bridge in case of disasters or extreme events. At the network level, the approach can be used for identifying high-risk bridges. This is possible because the approach correlates the condition of the bridge to the weakest link in the structure.

Limitations

This approach does not give a full picture of how deterioration is spread over the bridge. The total amount of defects (not the worst defect) is required for planning bridge maintenance repair and rehabilitation projects. Using this approach with weighted averaging methods is more helpful.

CHAPTER 5. QUALITATIVE METHODS

COMPUTATIONAL APPROACH OVERVIEW

Qualitative methods provide a direct, descriptive indication of the bridge condition rather than using a numeric scale. The index is assigned after extensive assessment of the condition of bridge elements using element-level inspection. A typical example of qualitative health index is the Bridge Health Indicator developed by Roads and Maritime Services in Sydney, Australia.

AUSTRALIA'S BRIDGE HEALTH INDICATOR

The bridge health indicator is used by Roads and Maritime Services for identifying bridges that need maintenance, repair, or rehabilitation, but it is not used for prioritizing projects. The bridge health indicator does not report the condition of a bridge on a numerical scale. It describes a structure as having an indicator of "Poor," "Fair," or "Good" based on the condition state and importance of the element under investigation. The element's importance is a reflection of the relative significance of the element to the overall performance of the structure. The significance or importance of an element is ranked as high, medium, or low. The element importance rankings are based on an expert determination of the proportion of similar elements that, if lost, will result in a collapse.(17) Table 25 describes how the overall bridge health is assessed based on the condition and importance of the elements.

Table 25. Bridge condition description based on element importance and condition states.

Bridge Health	Bridge Element Importance		
	High	Medium	Low
Poor	Percent in condition state 5 > 10 Percent in condition state 4 > 40	Percent in condition state 5 > 25 Percent in condition state 4 > 50	Percent in condition state 5 > 50 Percent in condition state 4 > 70
Fair	10 ≥ Percent in condition state 5 > 0 40 ≥ Percent in condition state 4 > 0	25 ≥ Percent in condition state 5 > 0 50 ≥ Percent in condition state 4 > 0	50 ≥ Percent in condition state 5 > 0 70 ≥ Percent in condition state 4 > 0
Good	0 percent in condition 4 or 5	0 percent in condition 4 or 5	0 percent in condition 4 or 5

As an example, an element of high importance with 15 percent of the element in condition state 5 is considered to be in "Poor" condition. An element of low importance with 50 percent in condition state 4 is considered to be in "Fair" condition.

AUSTRIA'S QUALITATIVE BRIDGE RATING

Although Austria has a BCI, most of the relevant infrastructure administrations do not use this calculation anymore but use simple ratings between 1 (no/minor damage) and 5 (critical condition).

Following the Austrian guideline for bridge inspections, the total rating of a bridge is based on the ratings of the bridge elements.(15) Each element is assigned a condition rating, ranging from 1 to 5 (table 26).

Table 26. Description of condition ratings for bridge elements in Austria's qualitative approach.

Rating	Description
1	No problems, minor problems; load-bearing capacity, operability, and durability not limited; no maintenance required.
2	Minor problems; load-bearing capacity and operability not limited; operability and durability will be limited if defects are not removed in the long-term; no restriction of use.
3	Moderate problems; indication of limited operability and durability; maintenance required in the medium term (within 6 years).
4	Severe problems; load-bearing capacity not yet limited but operability and durability already limited; maintenance within 3 years (short term) to reestablish regular use.
5	Critical condition; load-bearing capacity and operability limited; immediate initiation of repair, restriction of use.

On the basis of the bridge element ratings, the total rating of a bridge is also assigned a number from 1 to 5. The following factors are crucial for this classification:

- Extent/severity of damage.
- Limitation of load-bearing capacity, operability, and durability.
- Urgency of intervention.

STRENGTHS AND LIMITATIONS

Strengths

This approach is mainly used for general assessment of the bridge condition and identifying bridges that need maintenance. Qualitative methods rely on element-level inspection data and are able to provide a more objective assessment of the condition of structural elements by capturing both severity and extent of damages.

Limitations

This approach cannot be used effectively for prioritizing and planning rehabilitation and maintenance programs because it does not provide a quantitative scale for ranking bridges in a network. For example, many bridges may be rated as being in "Poor" condition with no particular ranking regarding which ones are in dire need of repair or replacement compared with others when only a few of them could be preserved or replaced due to budget constraints.

CHAPTER 6. OTHER METHODS

There are other BCIs that cannot be categorized into any one of the methods described in chapter 5. These indices use multiple approaches to calculate the overall BHI.

BRIDGE SR

The bridge SR was previously used in the United States for evaluating factors, indicating a bridge's sufficiency to remain in service, but was superseded as a result of the recent *Moving Ahead for Progress in the 21st Century Act* (MAP-21) legislation. The inspector rated each of the key components of the bridge by selecting a deterioration that best described the general condition of the component being inspected. The overall bridge rating was obtained by a weighted combination of the structural condition information and functional information. The SR approach was therefore an extension of the weighted averaging approach.

Data Inventory and Condition Rating

Bridge SRs were calculated by using data from NBI, which is a comprehensive database compiled by FHWA of all bridges with span lengths greater than or equal to 6.1 m on public roads. The database contains a collection of bridge information data items such as bridge identification or location, bridge type and specifications, operational conditions (i.e., age, average daily traffic, bypass, and detour length), bridge geometric or functional data (i.e., structure lanes, shoulder width, etc.), and bridge structural condition data (i.e., rating of deck, superstructure, and substructure). The SR was calculated using bridge functional, operational, and condition information.

Functional Information

Functional data provided an assessment of the level of service provided by the bridge. Examples of functional data in NBI include number of lanes, shoulder width, vertical under clearance (height of the bridge), etc. These data were also used by FHWA to rate or classify the service provided by a bridge. Bridges not meeting minimum clearance values (i.e., narrow lanes, narrow shoulders, inadequate vertical under clearance, etc.) were classified as functionally obsolete. A functionally obsolete bridge contained features below established limits. However, they may have been structurally sound and perfectly safe. In calculating SR, the bridge's serviceability and functional obsolescence contributed a maximum of 30 percent to the SR rating.

Operational Condition Information

The operational conditions of a bridge were based on the evaluation of factors such as average daily traffic, bypass, detour length, and highway designation. Operational conditions contributed a maximum of 15 percent to the overall SR.

Condition Information

The NBI database describes the structural condition of only key components of a bridge: the deck, the superstructure, and the substructure.

The bridge deck, which directly carries traffic, is inspected for defects such as cracking, scaling, spalling (for concrete decks), broken welds, broken girds, and section loss (for steel grid decks). Timber decks are inspected for splitting, crushing, fastener failure, etc. The condition of the bridge deck is rated based on the defects identified and in accordance with the general condition ratings in table 27. The superstructure that supports the deck and connects one substructure element to another is inspected for signs of distress, which may include cracking, deterioration, section loss, malfunction, and misalignment of bearings. The substructure supports the superstructure and distributes all bridge loads to bridge foundations. The substructure is inspected for visible signs of distress, including evidence of cracking, section loss, settlement, misalignment, scour, collision damage, and corrosion.

Table 27. NBI condition ratings.(18)

Rating	Description
9	Excellent condition.
8	Very good condition. No problems noted.
7	Good condition. Some minor problems.
6	Satisfactory condition. Structural elements show some minor deterioration.
5	Fair fondition. All primary structural elements are sound but may have minor section loss, cracking, spalling, or scour.
4	Poor condition. Advanced section loss, deterioration, spalling, or scour.
3	Serious condition. Loss of section and/or deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present.
2	Critical condition. Advanced deterioration of primary structural elements. Fatigue cracks in steel shear cracks in concrete may be present or scour may have removed substructure support. Unless monitored, it may be necessary to close the bridge until corrective action is taken.
1	“Imminent” failure condition. Major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic, but corrective action may put it back in light service.
0	Failed condition. Out of service and beyond corrective action.

The structural condition of a bridge’s key components (deck, superstructure, and substructure) is used to assess whether it is structurally deficient (NBI rating of 4 or less for deck, superstructure, or substructure). FHWA classifies a bridge as structurally deficient to indicate that the physical conditions of the bridge’s primary load-carrying elements have deteriorated. A “structurally deficient” bridge is not necessarily unsafe, but the owner may need to spend significant amounts on repair and maintenance to the keep the bridge in service, and the bridge would eventually require major rehabilitation or replacement to address the underlying deficiency.

Calculating SR

In calculating SR, the bridge's structural adequacy and safety together with the inventory loading contribute a maximum of 55 percent to the total rating.

The calculated SR (figure 24) is a function of four factors: structural adequacy and safety (A), serviceability and functional obsolescence (B), essentiality for public use (C), and special reductions (D), which is a maximum of 13 percent of the total rating. Elements considered include the detour length, traffic safety features, and main structure type.

$$SR = A + B + C - D$$

Figure 24. Equation. SR.

Uses of SR

Funding Eligibility

Previously, FHWA used SRs with a status flag, indicating whether a bridge is structurally deficient or functionally obsolete to decide on its eligibility for funding. A structurally deficient (or functionally obsolete) bridge with an SR less than 50 qualified for replacement, whereas a structurally deficient (or functionally obsolete) bridge with an SR greater than 50 but less than 80 qualified for rehabilitation.

RISK-BASED PRIORITIZATION FOR BRIDGES

Moon et al. proposed a risk-based method for prioritization of bridge repair and replacement projects in a network. This method provides the basis for a bridge prioritization tool being tested by NJDOT. Although this is a risk-based framework, because risk and resilience are critical components of bridge health and performance, this method is included in this synthesis to address that aspect of bridge health.(19)

The objective of this proposed method is to provide a risk-based approach that transportation authorities can use as a more transparent and objective approach to bridge evaluation and project prioritization. While the method appears qualitative in nature, it has distinct advantages over many current approaches. This approach defines *risk* as a product of hazards, vulnerabilities, and exposures and therefore explicitly recognizes key performance limit states. In addition, it incorporates the uncertainties associated with various assessment techniques, provides flexibility for their implementation, and provides a means to capture (in a useable format) expert knowledge and heuristics from top bridge engineers.

Definition of Risk

The proposed bridge assessment methodology is based on the concept of relative risk, which extends the reliability-based assessment approach to explicitly consider the consequences of not performing (in this definition called exposure). The inclusion of consequences is a necessary consideration for rational decisionmaking, and it is therefore imperative that consequences be included within the assessment procedure. The proposed framework takes into consideration a more partitioned definition for perceived relative risk (referred to as "risk" in this report) as a combination of hazard, vulnerability, exposure, and an uncertainty premium (figure 25).

$$\text{Perceiced Relative Risk (H)} = (\text{Hazard})\ (\text{Vulnerability})\ (\text{Exposure})\ (\text{Uncertainty Premium})$$

Figure 25. Equation. Perceived relative risk.

Where:

Hazard = Probability of a hazard occurring.

Vulnerability = Probability of failure (to perform adequately) given hazard.

Exposure = Consequences associated with a failure to perform adequately.

Uncertainty Premium = A factor to account for the level of uncertainty associated with the selected assessment approach, including the quality control measures employed.

Table 28 outlines some proposed hazards, vulnerabilities, and exposures for the four performance limit states to be considered by the proposed risk-based assessment approach.

Table 28. Summary of relevant performance limit states, hazards, vulnerabilities, and exposures for bridges.(19)

Performance Limit States	Hazards	Vulnerabilities	Exposures
Safety—geotechnical/hydraulic	• Flood plain. • Seismic design category. • Marine traffic. • Storm surge category. • Underwater substructure flowrate.	• Foundation bearing conditions. • Pier protection standards. • Scour critical. • Evidence of substructure settlement. • Superstructure above/below flood level.	• Replacement cost. • Coastal evacuation route. • Distance of detour route. • Strategic Highway Network route. • Utility disruption.
Safety—structural	• ADTT. • Seismic design category.	• Structural assembly classification. • Fatigue details. • History of displacements and vibrations. • Evidence of structural damage. • Spanned roadway functional classification. • Fracture critical details. • Exposed prestressing strands. • Rocker bearings.	Loss of life.

Performance Limit States	Hazards	Vulnerabilities	Exposures
Serviceability and durability	• ADTT of spanned roadways. • Average annual snowfall. • Use of deicing salts. • Freeze-thaw cycle. • Proximity to coast. • History of vehicular collisions.	• Water penetration/ corrosion. • Bearing conditions. • Expansion joint condition. • Condition rating of approach. • Condition rating of superstructure. • Condition rating of substructure. • Condition rating of deck. • Under clearance of spanned roadways.	Maintenance costs.
Operations	• History of fatal accidents. • Utilities on structure.	• Lane width. • Line striping condition. • Traffic safety feature adequacy. • Breakdown lanes/shoulders. • Percentage of legal truck weight posted.	History of congestion.

ADTT = Average daily truck traffic.

The framework scales the calculated risk using the Department of Homeland Security’s five-level risk scale (figure 26) in which “I” represents low risk level, and “V” represents severe risk level. This scale is easy to understand for both engineers and the general public.

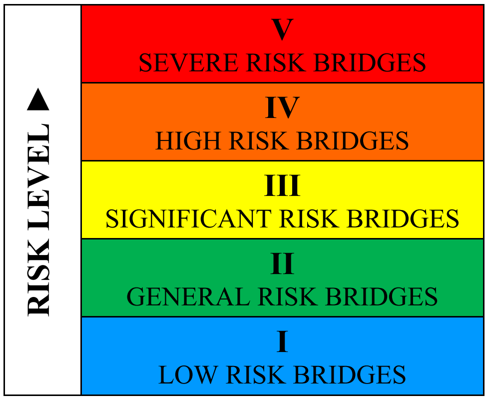

Figure 26. Chart. Risk scale for risk-based prioritization framework.

Risk-Based Assessment Framework

Moon et al. stress that the proposed framework is very rudimentary and needs to be refined based on expert elicitation and input from the many relevant professional organizations and committees.(19) While this framework has subjective components (due to the current lack of quantitative and objective data), as bridge performance research programs such as the LTBP Program expand their field data collection efforts, it is expected that this framework will become increasingly objective in nature by using data-driven inputs.(19)

Figure 27 shows a flowchart for the proposed risk-based prioritization. In this approach, the level of risk assessment is defined first, which identifies the acceptable uncertainty premium. After this definition, the estimation of relative risk is done by determining the hazard, vulnerability, and exposure of the bridge. The risk level is then calculated, which helps informed decisionmaking and budget allocation.

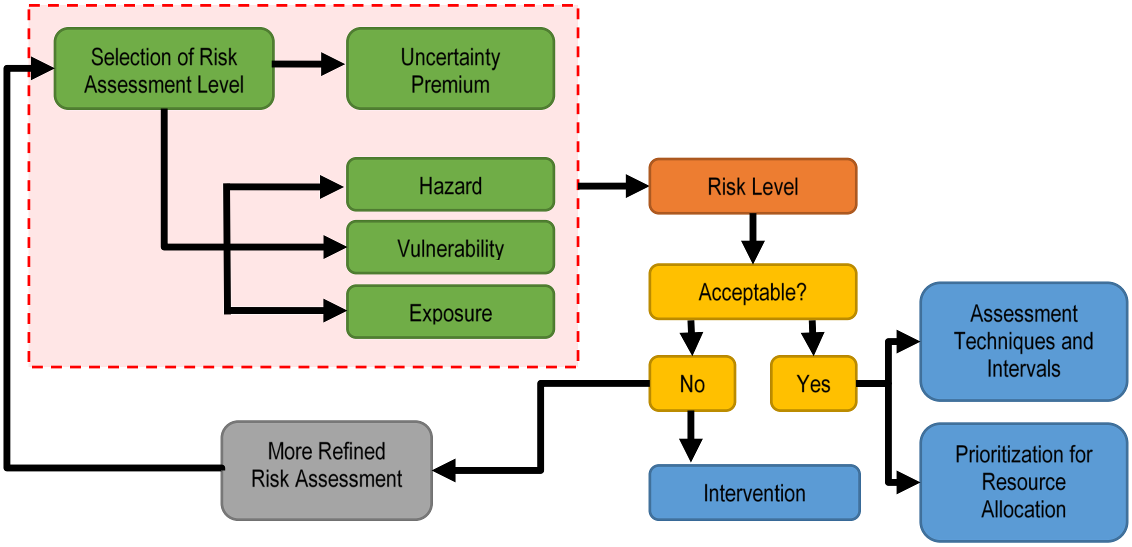

Figure 27. Flowchart. Proposed risk-based assessment framework.(19)

Uncertainty premiums associated with different levels of risk assessment are listed in table 29. The major deciding factor in the uncertainty premium is the level at which the risk is computed, whether at an aggregate level or divided up into individual risks. Although computing the risk in an aggregate level is more conservative and time efficient, it sometimes overestimates the actual risk drastically. In these cases, calculating a more realistic risk based on individual hazards as an accurate risk assessment can be worthwhile. The assessment levels reflect the specific approaches and technologies employed. More advanced analytical and experimental technologies are becoming available that can help users better understand the conditions of a structure and reduce the uncertainty premium. Also, a wide range of successful quality assurance programs have been developed. To recognize their influence and benefits, assessment levels that take advantage of these developments will have a lower uncertainty premium associated with them.

Table 30 through table 32 show how hazard, vulnerability, and exposure may be quantified for levels 1 and 2 assessments. In this case, the risks are groups in four categories: safety—

geotechnical/hydraulic; safety—structural; serviceability, durability, and maintenance; and operational and functional. For each of these categories, the hazard, vulnerability, and exposure are assigned a value of 1 through 3 based on location, structural and operational attributes, age, etc. The risk levels are then be calculated as discussed earlier in this section. Table 33 lists the preliminary risk levels.

Table 29. Risk assessment levels.(19)

Level	Example Approaches	Resolution	Quality Assurance	Uncertainty Premium
1	Visual Inspection, Document Review	Aggregate Risks	Minimum Standards	2.5
2	Visual Inspection, Document Review	Aggregate Risks	Best Practices	2.0
3	Visual Inspection, Document Review, Analytical Techniques	Individual Risks	Minimum Standards	1.5
4	Visual Inspection, Document Review, Analytical Techniques	Individual Risks	Best Practices	1.25
5	Visual Inspection, Document Review, Analytical and NDE Techniques	Individual Risks	Best Practices	1.0

NDE = Nondestructive evaluation.

Table 30. Preliminary hazard values for level 1 and 2 risk assessments.(19)

Hazards Considered		Hazard Values		
		1	2	3
Safety—geo/hydraulic	Scour, debris and ice, vessel collision, seismic—liquefaction, settlement, flood	Outside of a 500-year flood plain	Outside of a 100-year flood plain	Within of a 100-year flood plain
		Seismic design category A	Seismic design categories B and C	Seismic design categories D, E, and F
		Over a non-navigable channel	Navigable channel for mid-sized vessels	Navigable channel for large vessels
		Located more than 804 km from coast	Located more than 80.4 km from coast	Located within 80.4 km from coast
		No potential for scour	A rating of NBI item 113 (scour) of 7, 5, or 4	Not applicable
		No records of significant earthquake, floods, or storm surge	Records of moderate earthquake, floods, or storm surge	Observed drift and debris at piers/abutment history of ice flows in waterway

Hazards Considered		Hazard Values		
		1	2	3
Safety—structural	Seismic, fatigue, vehicle collision, overload, fire	Seismic design category A	Seismic design categories B and C	Seismic design categories D, E, and F
		ADTT less than 500	ADT less than 10,000	ADT more than 10,000
		Not spanning over a roadway	Spanning over a roadway with ADTT less than 1,000	Spanning over a roadway with ADTT more than 1,000/spanning a rail line
		Located more than 16 km from heavy industry	Located more than 16 km from heavy industry	Located less than 16 km from heavy industry
		No history of overloads, collision, or earthquake	Limited number of overloads or collision or minor earthquakes	History of overloads, collision, or severe earthquake
Serviceability, durability, and maintenance		No routine use of deicing salts	Moderate usage of deicing salts	High usage of deicing salts
		Located more than 100 mi from the coast	Located more than 25 mi from the coast	Located less than 25 mi from the coast
		Low number of freeze-thaw cycles	Moderate number of freeze-thaw cycles	Moderate number of freeze-thaw cycles
		No history of overloads	History of isolated overloads	History of repeated overloads and permits
Operational and functional		ADTT less than 1,000 and ADT less than 10,000	ADTT less than 10,000 and ADT less than 50,000	ADTT more than 10,000 and ADT more than 50,000
		No history of fatal accidents	History of isolated fatal accidents	History of repeated fatal accidents
		No history of congestion	History of moderate congestion	History of high congestion

Table 31. Preliminary vulnerability values for level 1 and 2 risk assessment.(19)

Vulnerabilities Considered	Vulnerability Values		
	1	2	3
Safety—geo/hydraulic	Founded on deep foundations or bedrock	Founded on shallow foundations on cohesive soil	Founded on shallow foundations or noncohesive soil
	No history and no evidence of scour or settlement	Evidence of minor scour/undermining during past/present underwater inspections	Evidence of moderate to significant scour/undermining during past/present underwater inspections
	Meets current pier impact and scour protection standards	Pier protection system in good condition	Pier protection system missing or in poor condition

Vulnerabilities Considered	Vulnerability Values		
	1	2	3
	Superstructure above 100-year flood level	Superstructure above 100-year flood level	Superstructure below 100-year flood level
	No tilt of substructure elements	Minor tilt of substructure elements	Significant tilt of substructure elements
Safety—structural	Meets all current design specs	Does not meet all current design specs, but most of them	Noncomposite construction
	Structure displays bi-directional redundancy	Simply supported constructed with transverse distribution capabilities	Simply supported construction with minimal transverse distribution capabilities
	20 years or less since construction or major renewal	50 years or less since construction or major renewal	50 years or more since construction or major renewal
	A and B fatigue details	C and D fatigue details	E and E' fatigue details
	Elastomeric bearings	Steel bearings	Rocker bearings, intrinsic force dependency, exposed prestressing strands, and pin and hanger details
	No evidence of structural damage	Minor evidence of structural damage within the critical load path	Evidence of structural damage within the critical load path
	Clearance more than 15.2 cm of current standard	Clearance within 15.2 cm of current standard	Clearance below current standards
	No history of excessive displacements or vibrations	History of significant displacements or vibrations	History of excessive displacements or vibrations
	Substructure elements plumb	Substructure elements within 10 percent of plumb	Substructure elements more than 10 percent of plumb

Vulnerabilities Considered	Vulnerability Values		
	1	2	3
Serviceability, durability, and maintenance	No visible cracks	Minor local cracking	Extensive cracking and spalling
	No evidence of reinforcement corrosion	Some evidence of reinforcement and structural steel corrosion	Evidence of widespread reinforcement and structural steel corrosion
	Paint in good condition	Paint in moderate condition	Paint in poor condition
	Elastomeric bearing	Steel bearing	Frozen bearings and exposed prestressing strands
	Joints in good operating condition	Joints with minor evidence of leaking	Failed expansion joints
	Approach does not display rutting	Approach displays minor rutting	Approach displays significant rutting
	Scuppers are less than 10 percent clogged	Scuppers are between 10 and 50 percent clogged	Scuppers are between 50 and 100 percent clogged
Operational and functional	Roadway approach alignment and bridge geometry up to current standards	Lane width within 0.3 m of current standards	Lane width more than 0.3 m less than current standards
	Guard rail and road paint in good condition	Guard rail and road paint in fair condition	Guard rail and road paint in poor condition
	Not posted	Posted for more than 90 percent of legal truck weight	Posted for less than 90 percent of legal truck load
	Good ride quality of deck	Moderate ride quality of deck	Poor ride quality of deck
	Breakdown lane/shoulders	Breakdown lane/ shoulders not present	Breakdown lane/shoulders not present
	No rutting of pavement	Minor rutting of pavement	Significant rutting of pavement

Table 32. Preliminary exposure levels for level 1 and 2 risk assessments.(19)

Exposure Considered	Exposure Values		
	1	2	3
Safety—geo/hydraulic Safety—structural	ADT less than 10,000	ADT less than 50,000	ADT more than 50,000
	Replacement cost less than $2 million	Replacement cost less than $10 million	Replacement cost more than $10 million
	Not on a critical route (life line, evacuation route, etc.)	Not on a critical, nonredundant route (life line, evacuation route, etc.)	On a critical, nonredundant route (life line, evacuation route, etc.)
	Detour route less than 8 km	Detour route less than 16 km	Detour route more than 16 km
Serviceability, durability, and maintenance	Low maintenance costs	High maintenance and repair costs	N/A
	ADT less than 50,000	ADT more than 50,000	
Operational and functional	No history of congestion	Average peak hour delays of more than 10 min	N/A
	ADT less than 25,000	ADT more than 25,000	
	ADTT less than 10,000	ADTT more than 10,000	

N/A = Not applicable.

Table 33. Preliminary risk levels.(19)

Risk Level	Threshold Risk Values
Level V: Severe risk bridges	> 40
Level IV: High risk bridges	30–40
Level III: Significant risk bridges	20–30
Level II: General risk bridges	10–20
Level I: Low risk bridges	< 10

In order to translate risk levels into appropriate actions, assessment techniques, and required intervals for assessments, a set of minimum requirements and optional assessment programs is needed. A preliminary estimate of this relationship is shown in table 34.

Table 34. Preliminary assessment programs per risk level.[19]

Risk Level	Mandatory	Option 1	Option 2
Severe	Level 3 / 1 Year	Level 4 / 18 months	Level 5 / 2 years
High	Level 2 / 1 Year	Level 4 / 2 years	Level 5 / 3 years
Elevated	Level 2 / 2 years	Level 4 / 3 years	Level 5 / 4 years
Guarded	Level 1 / 2 years	Level 4 / 4 years	Level 5 / 6 years
Low	Level 1 / 2 years	Level 4 / 4 years	Level 5 / 6 years

Note that the acceptable risk level that triggers more refined risk assessment and also relative quantitative values for uncertainty need to be calibrated based on case studies and expertise of experienced engineers.

Strengths and Limitations

Strengths

The proposed approach recognizes the diverse set of performance limit states relevant to management decisions and can readily be incorporated within risk-based decision-support tools. While this framework remains highly qualitative and subjective in nature, it has the advantage of requiring very limited changes on the actual practice of bridge inspections, and it can be implemented for most bridges using current inspection data and other publicly available data sources.

This approach not only provides decisionmakers with a more complete picture of the uncertainty associated with various assessment procedures, but it also promotes the use of more reliable approaches while still providing States some freedom regarding implementation depending upon their individual priorities and concerns.

Limitations

Although calculating actual risks assocated with bridges is ideal, it is not possible in practice. For this reason, performance-based risk methods yield a perceived risk, which is valuable in a relative sense.

The proposed framework adopts key performance limit states (safety; durability, serviceability, and maintenance; and operations and functionality), including State or regional costs associated with operation, evaluation, maintenance, and repair. Bridge performance is a more complex concept, and performance of a bridge may cover other limit states that are not fully known. It is expected that as this assessment procedure matures and the findings of the LTBP Program are released, additional performance limit states may be included, and some of these performance limit states may be subdivided to allow for a higher resolution assessment.

CHAPTER 7. CONCLUSIONS

This synthesis discussed state-of-the-art bridge condition or health indices being used to assess performance of bridges in the United States and other countries. Current methods for developing condition or health indices were grouped into four different approaches based on the computational methods used. A discussion on each approach covered the data required for computing the index and the strengths and limitations of the approach.

The majority of health indices are designed to help stakeholders plan for bridge maintenance and rehabilitation activities. This is typical among weighted averaging and ratio-based approaches, which calculate the overall health index by combining all defects identified at the element level. Other health indices, such as the worst-conditioned component index, are more interested in identifying weak links within the bridge structure that could severely affect the safety and durability of the bridge in case of a disaster. They are frequently used together with weighted averaging methods. Most systems rely on a qualitative approach to assess bridge health and performance. Qualitative methods are essential for general assessment of the bridge condition and identifying bridges that need maintenance.

With the exception of the recently supplanted SR, all other BMSs rely on element-level inspection data to obtain the overall BHI. The use of element-level inspection data provides a more thorough assessment of the condition of the bridge. It also provides a more objective evaluation of the bridge's condition because it reduces reliance on inspector's judgment for rating the condition of the bridge. Element-level inspection enables inspectors to capture both the severity and extent of any problems that may influence the integrity of the structure. Such information is valuable for planning maintenance, repair, and rehabilitation programs.

A key recurring limitation identified is the lack of accurate and objective data used to compute the condition indices. Visual inspection remains the predominant approach for assessing the condition of bridge elements. Since this heavily relies on human judgment, the possibility of one inspector rating the condition state of an element differently from another inspector is likely. Therefore, a true assessment of the condition of bridge elements is difficult and uncertain since the data acquired is sensitive to the inspector's expertise and sound judgment. The use of expert opinion and engineering judgment, as reflected in assigning weights and defining the relative importance of an instance of damage or an element, plays a key role in the estimation of condition indices. Opinions about the criticality of an instance of damage or a bridge element to the overall structure is highly variable. Using engineering judgment alone may introduce subjectivities into the estimation. Therefore, it is safe to conclude that with the current visual inspection approach to acquiring bridge condition data, the possibility of subjective and imprecise data entering the estimating process is present. The development of condition indices should be driven by more objective and quantitative data, which will help bridge managers make data-driven decisions.

Studying the basis for the BHIs used around the world also shows that most indices do not consider operational, safety, and lifecycle cost performance metrics and mostly rely on condition states of the bridge's elements or components. It is important that an effective performance-based health index includes metrics at different limit states such as utility, operations, serviceability, structural, maintenance, safety, resilience, traffic, financial, and environmental.

It should be noted that subjectivity in BHIs will never diminish because some qualitative performance metrics always require some level of engineering judgment or input, such as condition ratings assignments to bridge elements. Currently, FHWA is establishing research-oriented protocols for data collection during bridge assessment, inspection, NDE, and field testing. These protocols could be leveraged in reducing subjectivity when assigning qualitative metrics.

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