Sensitivity Analysis of Bridge Health Index to Element Failure Costs and Conditions

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Bridge Health Index (BHI) is a bridge performance measure based on the condition of the bridge elements. It is computed as the ratio of remaining value of the bridge structure to the initial value of the structure. Since it is expressed as a percentage value, the BHI could provide an intuitive measure for bridge engineers, and legislators. The BHI could be converted to another measure such as color (red, yellow and green) that public understands better. The Pontis user group was surveyed to determine the current use of the BHI and other measures for bridge management decision making.

This study focused on understanding the sensitivity of the BHI to small and large changes in the element failure costs and the element condition, the two input data sets for computing the BHI. For these sensitivity analyses, 221 bridges were selected from Wisconsin's inventory. The study looked at bridges with simple and continuous span prestressed concrete girders. The findings can guide state agencies and practitioners with a sense of how BHI responds to changing bridge condition as well as element failure costs.

The element failure costs were acquired from a previous study by a consultant to the FHWA and the element level inspection data were from the Wisconsin Department of Transportation (WisDOT).

The analysis considered the impact of Smart Flags used to identify local problems that are not reflected in the element condition states. Because they may indicate critical defects in the bridges, they should be reflected for BHI. To investigate the impact of Smart Flags, computation rules suggested by the Kansas DOT were applied to the selected bridges in Wisconsin.</td></tr>
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EXECUTIVE SUMMARY

Bridge Health Index (BHI) is a bridge performance measure based on condition of the bridge element. BHI is a somewhat new measure that is being used at some state highway agencies. It is computed as that ratio of remaining value of the bridge structure by the initial value of the structure. Since it is expressed as a percentage value, the BHI could provide an intuitive measure for bridge engineers, legislators, and the public.

The Pontis bridge management system has built-in tools for computing the BHI and thus states using Pontis are most likely to use the BHI as a performance measure. The Pontis user group was surveyed to determine the current use of the BHI and other measures for bridge management decision making. The survey results revealed that State Departments of Transportation (DOT) are employing several bridge performance measures, including the BHI, depending on the type of project decision. The National Bridge Inventory (NBI) condition rating and sufficiency rating are the most commonly used measures for preventive maintenance[1] projects. NBI rating, structurally deficient classification, sufficiency rating, and load rating are other common measures for bridge management decision making. BHI is as commonly used as the other measures, but it is being used for predicting the condition of a specific structure, and for prioritizing projects at the network level. There are no standards or guidelines for making decision based on the BHI. Since BHI is relatively new, there is limited experience among states for using it. Bridge managers do not have an intuitive understanding of how the value of the BHI responds to changes in bridge element conditions.

This study focused on understanding the sensitivity of the BHI to small and large changes in the element failure costs and the element condition, the two input data sets for computing the BHI. The sensitivity analyses focuses on 221 bridges located in Wisconsin DOT District 1 (now Southwest Region). The study looked at bridges with simple and continuous span prestressed concrete girders. The element failure costs are from the spreadsheet method for computing the minimum failure costs developed for the Federal Highway Administration[2] and posted on the ASHTO Transportation Asset Management Today website, and the element level inspection data were from the Wisconsin Department of Transportation (WisDOT).

The analysis considered the impact of Smart Flags[3] used to identify local problems that are not reflected in the element condition states. Because they may indicate critical defects in the bridges, they should be reflected for BHI. To investigate the impact of Smart Flags, computation rules suggested by the Kansas DOT were applied to the selected bridges in Wisconsin.

A simulation approach was applied to conduct the sensitivity analyses by randomly changing

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[1] For purpose of this study, preventive maintenance is defined as a cost-effective means for extending the service life of a bridge. Treatments that increase structural capacity are not considered preventive maintenance.

[2]Developed by Al-Wazeer of B.D. Systems. AASHTO Transportation Asset Management Today. (accessed, December 21, 2009). http://assetmanagement.transportation.org/tam/aashto.nsf/docs/E5D2A9F05323691185256B3A004E0632?opendocument&CurrentCategory=c.%20Management%20Systems

[3] Smart Flags in the Pontis Bridge Management System provide additional condition information that aisre not reflected in the CoRe element condition state language.

one parameter while fixing the other. The analysis explored random variations from three different ranges of a truncated triangular distribution: ±10%, ±20%, and ±50% of the deterministic values. The research results of the sensitivity analyses are summarized below.

- The sensitivity analysis was conducted for bridges grouped by simple and continuous span prestressed concrete girders. The analysis considered the individual groups. Comparisons across the groups showed consistent results.
- The BHI is far more sensitive to element condition than to element failure cost. This is good news since estimates of element failure costs are more uncertain than bridge condition from element inspection.
- BHI is increasingly sensitive to the element failure costs as bridge conditions worsen. Random uncertainty in individual element failure costs can significantly impact the BHI when bridges are in poor condition. Since the procedure to calculate the BHI is a weighted average, any change in the failure cost will change the outcome. If the failure cost of all elements change by a constant percent, there will be little change in the BHI. The bulk of the computation is in the number of condition states and percent of elements in each state.
- Even small changes in distributions of elements among condition states can significantly affect the BHIs. The more the element quantities are perturbed, the greater the variation in BHI. The BHI successfully reflects the bridge condition even if element failure costs are roughly estimated.
- For prioritizing among bridges in poor condition, the BHI may not be a robust criterion because small changes in the elements' failure costs lead large changes in the BHI. This could influence the priority order. When bridges are in poor condition, the range of the BHI is too small and very dependent on the failure cost. On the other hand, the BHI is a more robust measure when bridges are in good condition because large variations in element failure cost have little influence on BHI.
- The effect of Smart Flags can considerably lower the BHIs. The analysis used Smart Flag rules from the Kansas DOT. It is highly recommended that State DOTs develop rules to integrate Smart Flags when computing BHIs. The Smart Flag rules may vary with environmental circumstances and importance of the bridge components.

The BHI offers a measure that directly reflects the element level condition data collected in the field. Even small changes in the distributions of element conditions will influence the computed BHI. If states adopt the BHI as a measure for decision making, they should make every effort to keep reliable element level inspection records. BHI is less sensitive to element failure cost, but for consistency, State agencies should make efforts to establish reliable element failure costs.

By studying the trends for BHI over time, agencies may be able to create reliable bridge deterioration curves and to consistently estimate the benefits of bridge preservation actions. The investigations can help establish the thresholds defined by BHI for bridge preservation, such as preventive maintenance, rehabilitation, and reconstruction. Moreover, ongoing evaluation of the guidelines assures the BHI will be an accurate indicator for measuring the bridge condition, for allocating preservation budgets, and for communicating with the public.

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1 INTRODUCTION

1.1 Motivation

Performance measures are essential for a successful bridge management system. They allow highway agencies to assess and predict bridge condition as well as to diagnose deterioration mechanisms and to specify maintenance and preservation treatments accordingly. The right preservation treatment to remedy the problem originates from precise bridge condition assessment by proper performance measurement. Moreover, consistent and reliable performance measurements also allow the appraisal of long term bridge programs or bridge policy *(1)*. Performance measures are also tools to communicate with legislatures, agency executives, other bridge managers, and especially the public.

The Bridge Health Index (BHI) is a bridge performance measure initially developed by the California Department of Transportation (Caltrans) *(2)*. It is attractive because it is a single-number assessment, expressed as a percent value, of a bridge's health based on the condition of its structural elements *(3, 4)*. The number provides an assessment of the remaining value of the structure. While the functions to compute BHI are available in the Pontis Bridge Management System (BMS), many State agencies are not using the BHI. One possible reason is that the state agencies do not have the sufficient data required to compute the BHI. Most states, including Wisconsin, have the element level inspection records, but many have not established the necessary element weight factors for calculating the BHI. Another possible reason is that the BHI is relatively new, and familiarity with it is still growing. Bridge managers may have an intuitive understanding of how the value of the BHI responds to changes in bridge element conditions but other decision makers may not. A more intuitive system may be to equate bridge condition in terms of BHI to a color scheme. For example, BHI of more than 90 would be green for good condition, between 80 and 90; would be yellow for fair condition and less than 80 would be red for poor condition. Without an intuitive system, agencies may refrain from using the BHI in their bridge management decision making.

1.2 Objectives and Research Approach

The initial goal of the project was to develop guidelines for using the BHI. Bridge managers need to be able to equate BHI to something they are familiar with. For example, guidelines for equating BHI values to condition levels good condition (green), fair condition (yellow), and poor condition (red). The Wisconsin Department of Transportation (WisDOT) has one of the necessary data sets, element conditions, for computing the BHI, but not the other data set, element weight factors. There are two element weighting options available for BHI calculation and they are element failure cost and relative weight of the element. Neither is available for bridges in Wisconsin. After consulting this project's technical committee and the WisDOT technical liaison, the project's focus was adjusted to concentrate on the usage of the BHI in other State DOTs and the sensitivity of the computed BHI to its input parameters of bridge element weight factors and bridge element conditions.

The primary goal is to consider the BHI for decision making. The project accomplishes this goal by investigating the sensitivity of the BHI to Wisconsin's bridge element conditions and adopted failure costs, which are the primary parameters for computing BHI. To achieve the goal, the research team conducted three tasks.

The first task was to review the status of the BHI and other bridge performance measures for bridge management decision making. This task included reviewing data sources and ways to compute the BHI. The researchers conducted a survey of State Highway Agencies to assess the use of the BHI as a performance measure. The survey was sent to members of the AASHTO Pontis user group.

The second task was to analyze the sensitivity of the BHI to uncertainty in the estimates for element failure costs and conditions. The results of this task show the feasible values of the BHI for the expected ranges of the input parameters. The values for element failure costs came from a previous study *(5)* conducted by an FHWA contract employee and the bridge element conditions were provided by WisDOT.

The third task was to analyze the influence of the Pontis Smart Flags, used to modify element condition, when calculating BHIs. Since WisDOT does not have rules for applying the Smart Flags , the Kansas DOT's Smart Flag rules were used to adjust the BHIs of bridges in Wisconsin.. The BHIs considering Smart Flags were compared to those without Smart Flags. The results can give a sense of the importance of considering Smart Flags when calculating BHI.

The results of this study are expected to help the WisDOT and other highway agencies understand the BHI and its potential use in decision making.

1.3 Organization of the Report

The report is organized into several sections:

Section 2. Indexes for Bridge Performance Measurement – Presents the review of various performance measures for bridge management decision making include the bridge health index.

Section 3. State Survey on Bridge Performance Measures – Describes the results of the survey. It contains the list of states that are using BHI for their bridge management system as well as how they employ it.

Section 4. Bridges and Failure Costs for the Sensitivity Analysis – Explains the data set used for sensitivity analysis. Two essential components are described: the element failure costs and the element condition.

Sections 5 and 6. Sensitivity Analysis of BHI to Element Failure Cost and Element Condition – Presents and interprets the results of the sensitivity analyses.

Section 7. Incorporating Element Smart Flags – Shows how BHIs can be impacted by integrating Smart Flags. The rules used in Kansas DOT are applied to adjust BHIs in Wisconsin.

Section 8. Summary and Recommendations - Provides a summary of the findings and offers suggestions for using the findings for State agencies.

Appendices – Includes the list of CoRe element with description, survey documents, and Kansas DOT rules to apply Smart Flags for BHI.

2 INDEXES FOR BRIDGE PERFORMANCE MEASUREMENT

This section reviews the performance measures and indexes used by State highway agencies for managing bridges. The choice of performance measure depends on the decision being made and other factors such as agency policy, standard practice, bridge type, scope (network or project), and stakeholder concerns *(1)*.

Specifically for the Bridge Health Index (BHI), this section presents a definition, required components for computing, and the potential uses in bridge management decision making. Furthermore, the use of the BHI is compared to other bridges performance measures.

2.1 Bridge Health Index (BHI)

California DOT developed the Bridge Health Index (BHI) to be a bridge performance measure for communication with management, elected officials and the public *(4)*. The California BHI is a single-number indicator of a bridge's condition expressed as a percentage *(3)* of the bridge's economic worth *(2)*. It is calculated from an element-level inspection as a ratio of the current to the initial value of all elements on the bridge. BHI may range from 0%, corresponding to the worst possible health, to 100% for the best possible health.

The premise of the BHI is that each bridge element (when new) has an initial asset value in the best condition state (CS). After construction, an element may deteriorate to a lower condition state due to accumulated traffic, environment, design or construction flaws. Each element loses asset value over time. After repair, preservation or rehabilitation, the condition of an element is improved and it regains some asset value *(6)*.

The availability and quality of bridge element inspection data are required for calculating the BHI to reflect the bridge's condition. Element-level inspection requires individual condition assessments for each element such as girders, floor beams, and pin and hanger assemblies. Typically, inspectors rate each element of a bridge according to three, four or five condition states: protected (1), exposed (2), attacked (3), damaged (4), or failed (5), depending on the type of element *(4)*. Concrete decks, for example, are rated using five condition states, while reinforced concrete columns are rated using four condition states. The inspector distributes the total quantity of the inspected element among the different condition states of the element.

There are three types of bridge elements: AASHTO Commonly Recognized CoRe elements, Non-CoRe elements and Smart Flag *(7)*. The description of each element type and examples are listed in Table 1. The complete list of the bridge elements defined by the American Association of State Highway and Transportation Officials (AASHTO) is included in Appendix B.

To aggregate the element level condition to bridge level condition, weights are assigned to the elements according to the economic consequences of element failure. The choice of failure cost is a function of models for optimal actions. The usefulness of the FC is to scale the magnitude of elements in relation to each other (i.e. girders have more weight that bearing).Thus, elements whose failures have relatively little economic effect, such as a railing, receive less weight than elements whose failure could close the bridge, such as girders *(4)*. There are two methods for assigning weight to each element, and both are used in Pontis. One method is to calculate the weight based on the element failure cost as the sum of the agency and user failure cost components. The other method is to directly assign the weight coefficient to each element *(3)*. For the latter method, the weight coefficients are usually determined by bridge engineers in the state DOT and are typically equal to the element replacement cost.

Table 1. Types of Bridge Element

Element Type	Description	Examples
CoRe	Bridge elements that are nationally recognized and used	Girders, trusses, arches, cables, floor beams, stringers, abutments, piers, pins and hangers, culverts, joints bearings, railings, decks, and slabs
Non-CoRe	Bridge elements that are not included in the CoRe elements	Tunnels, rigid frames, slop protection, wingwalls and headwalls, lateral bracing of trusses, diaphragms, connectors for steel elements, waterway protection, cap with epoxy coated reinforcing
Smart Flag	Additional information about the condition of an element to identify local problems that are not reflected in the CoRe element condition state language	Steel fatigue, pack rust, deck cracks soffit (underside of deck), settlement, scour, traffic impact damages, section loss of steel members

The BHI can be computed for a single element or for an entire bridge. The BHI of an individual element is calculated using Equation 1.

$$H_e = \frac{\sum_s k_s q_s}{\sum_s q_s} * 100\%$$

Equation 1. BHI for a single element.

Where, H_e = health index of the individual element, s is the index for the element's condition states, q_s = quantity of the element in condition state, s, and k_s is a coefficient corresponding to the s^{th} condition state.

The coefficient for each condition state is a fractional value that is calculated as shown in the heading for Table 2. The health index coefficients are given in the table.

Table 2. Condition state coefficients for computing the Bridge Health Index

n = applicable number of condition states	$k_s = \frac{n-s}{n-1}, s = 1, 2, ..., n$				
	k_1	k_2	k_3	k_4	k_5
3	1.00	0.50	0.00		
4	1.00	0.67	0.33	0.00	
5	1.00	0.75	0.50	0.25	0.00

$$BHI = \frac{\sum_e H_e Q_e W_e}{\sum_e Q_e W_e}$$

Equation 2. Bridge Health Index

The health index of an entire bridge is calculated as a weighted average of the health indexes of its elements (Equation 2). The elements are weighted by their total quantity and relative importance.

Where, e is the index for the bridge's elements, Q_e = total quantity of the element e, and W_e = weighting factor for element e.

The California BHI is using an "element failure cost" as the weight factor *(2)*. The formula is shown in Equation 3. Using the weight factors equivalence, California's BHI is the same as the BHI from Equation 2.

$$BHI = \frac{\sum_e Current\ Element Value}{\sum_e Total\ Element Value} = \frac{\sum_e \left(W_e * \sum_s k_s\, q_s \right)}{\sum_e \left(W_e * \sum_s q_s \right)}$$

Equation 3. California's BHI

Where, e is the element index, s is the condition state index, W_e = the weighting factor, which is the failure cost (FC), for element e, q_s = the quantity of element e in condition state s, and k_s = health index coefficient corresponding to the s^{th} condition state.

A review of the literature reveals the diverse applications of the BHI in bridge management. Obviously, it may be used for quantifying element condition as well as full bridge condition. It also can be applied to the network level bridge management. Caltrans suggests uses of the BHI for allocating resources, for managing budgets, for evaluating district-level performance on maintenance and rehabilitation, as a level-of-service (LOS) indicator, and for communicating with the public and legislature *(2)*. The BHI is also being used to inform the staff of the allocation process and in the annual maintenance performance evaluation report *(4)*.

The BHI may be used to predict the health of an inventory in future years when combined with deterioration rates based on funding levels. Robert et al. suggests that BHI may be used to quantify the benefit of bridge preservation actions that are not included in the maintenance policy *(8)*. Pontis Release 3 computes preservation benefits as the savings accrued by following the action that is recommended by the optimal preservation policy. Pontis Release 4 uses the change in BHI as the default method for calculating preservation benefits. The benefit of a preservation project is proportional to the difference in the BHI before and after the project as shown in Equation 4.

$$B = \frac{\Delta BHI \sum_e Q_e W_e}{100}$$

Equation 4. Benefit of a Bridge Preservation Project

Where, B = (annual) benefit of performing a preservation project, ΔBHI = change in Bridge Health Index due to preservation maintenance, e is the element index, Q_e = total quantity of element e, and W_e = weighting factor, which is the failure cost (FC), of element e.

To find out the actual applications of BHI, a survey was sent to the Pontis user group. The survey questions included how the state DOTs are using BHIs as a bridge performance indicator. The detailed results of the survey are documented in the next section.

2.2 National Bridge Inventory (NBI) condition ratings

Since the establishment of the National Bridge Inspection Standards (23 U.S.C. 151) , in place since the early 1970s and the National Bridge Inventory (NBI), which has bridge inspection entries since 1983, the Federal Highway Administration has monitored the condition of the nation's bridges. States report the NBI data annually as required by 23 U.S.C. 151 and describe in the Federal Recording and Coding Guide *(9)*. The Coding Guide defines 95 specific data items describing a bridge location, geometrics, age, traffic, load capacity, structural condition, and other relevant features. The NBI condition rating reflects the range of the physical condition of the major bridge components such as deck, superstructure, substructure, culvert, and sub-elements (piers, abutments, piles, etc.). The NBI defines condition states on a scale of 0 to 9 (see Table 3) *(9)*.

Table 3. NBI Condition State Rating

Condition State	Condition	Physical Description
9	Excellent	A new bridge
8	Very good	No problem noted
7	Good	Some minor problem
6	Satisfactory	Structural elements show some minor deterioration.
5	Fair	All primary structural elements are sound but may have minor section loss, deterioration, spalling or scour.
4	Poor	Advanced section loss, deterioration, spalling, scour
3	Serious	Loss of section, etc. has affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	Critical	Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed structural support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	Imminent Failure	Major deterioration or loss of section in critical structural component or obvious vertical or horizontal movement affecting structural stability. Bridge is closed to traffic but corrective action may put back in light service.
0	Failed	Out of service. Beyond corrective action

NBI condition rating does not represent the overall condition of an entire bridge, but shows the localized condition of the major bridge elements. The NBI indicates how well the major elements of a bridge function, not how well the whole bridge functions. This may make it difficult for state agencies to evaluate the overall bridge condition, and to use it for their network level bridge management system. Moreover, the NBI rating provides information on the severity of a condition but does not identify or quantify the extent of the problem. Also, like any rating system that involves inspector's judgment, the NBI is vulnerable to subjective interpretation by inspectors, who have to decide which distress symptom most represents the bridge condition when multiple distress symptoms may adversely affect the ratings *(2)*. NBI's multiple distress symptoms may not be a liability. There is an ongoing discussion within the bridge community and AASHTO committees about the benefits of multi-path deterioration inspection criteria versus the current CoRe system.

2.3 Sufficiency Rating (SR)

The NBI coding guide includes a procedure to calculate a bridge's Sufficient Rating (SR), which combines the functional and condition data in the NBI into a single number from 0 to 100. SR is calculated by combining four separate factors (Table 4) to obtain a numeric value for the bridge's sufficiency to remain in service. SR is calculated as $SR = S_1 + S_2 + S_3 - S_4$.

Table 4. Factors for Calculating Sufficiency Rating (SR)

Factor	Maximum	Consideration
Structural adequacy and Safety (S_1)	55%	• Superstructure • Substructure • Culverts • Inventory rating
Serviceability and functional obsolescence (S_2)	30%	• Lanes on structure • Average daily traffic • Approach roadway width • Structure type • Bridge roadway width • Vertical clearance over deck • Deck condition • Structural evaluation • Deck geometry • Under Clearance • Waterway adequacy • Approach roadway alignment • Highway designation
Essentiality for public use (S_3)	15%	• Detour length • Average daily traffic • Highway designation
Special reductions (S_4)	13%	• Detour length • Traffic safety features • Structure type

FHWA uses the SR to allocate funds for the Highway Bridge Rehabilitation and Replacement Program (HBRRP) and in determining eligible criteria for bridge projects that use these funds *(2)*. HBRRP was renamed the Highway Bridge Program (HBP) in 2008 by passage of the SAFETEA-LU technical correction bill (Public Law No. 110-244, 122 Stat. 1572) and the SR is still among the criteria used to determine federal funding eligibility *(10, 11)*. If a bridge's SR is less than 50 and is classified as deficient, the bridge is eligible for replacement. If SR is within 50 and 80 and the bridge is classified as deficient, it is eligible for rehabilitation. SR is a composite measure based that combines both function and condition. The rating emphasized large-scale functional and geometric characteristic and not meant for determining a bridge's overall condition or for maintenance decisions *(12)*.

2.4 Structural Deficiency and Functional Obsolescence

Bridges are classified as "structurally deficient (SD)" if they have a NBI rating for the deck, super structure, substructure or culvert of 4 or less (see Table 3) or if the approach roads regularly flood *(13)*. Though structurally deficient bridges do not imply that they are unsafe, they do need preservation, repair and eventually rehabilitation or replacement to address the deficiencies. In many cases, structurally deficient bridges are posted to restrict the gross weight of vehicles so the bridge can remain open to traffic.

In general, bridges are classified as "functionally obsolete (FO)" if they were built to standards that do not meet the minimum Federal clearance requirements of a new bridge *(13)*. Functionally obsolete bridges include those that have sub-standard geometric features such as narrow lanes, narrow shoulders, poor approach alignment or inadequate vertical under clearance. The functionally obsolete classification is also used for prioritizing within the Federal bridge replacement and rehabilitation funding program.

2.5 Geometric Rating

Geometric rating is an overall rating for deck geometry based on two NBI items: bridge roadway width (NBI Item-51) and vertical over-clearance (NBI Item-53). The geometric rating varies from 0 to 9 as NBI rating scale. NBI condition state rating is described in Table 3.

2.6 Load Rating

Load rating is used to determine the live load weight that structures can safely carry. Bridges are rated at three different levels, referred to as Inventory Rating, Operating Rating, and Posting Rating *(14)*. The load ratings are described in Table 5.

Table 5 Three Stress Levels for Load Rating

Load Rating	Description
Inventory Rating	Live load for the vehicle type used in the rating that will result in a load level which can safely utilize an existing structure for an indefinite period of time.
Operating Rating	Absolute maximum permissible load level to which the structure may be subjected for the vehicle type used in the rating.
Posting Rating	Live load for the vehicle type used in the rating that will result in a load level which may safely utilize an existing structure on a routine basis for a limited period time.

Structural capacity and loading are used to analyze critical members to determine the appropriate load rating for a bridge. This may lead to load restrictions on the bridge or identification of components that require rehabilitation or other modification to avoid posting of the bridge. Though the load rating does not indicate the overall condition of the bridge, it can reflect problems with the load carrying structural member such as the beams and girders.

2.7 Vulnerability Rating (VR)

New York State DOT uses a vulnerability rating (VR), which is the sum of a likelihood and consequence score *(15)*. The subjective measures for likelihood (high, medium, low, or not vulnerable) are based on a classifying process that is specific to the type of vulnerability being considered. For example, if the bridge is exposed to low vulnerability, the likelihood score is 2. The consequence score is based on the type of bridge failure (catastrophic, partial collapse or structural damage) and the exposure to the public from that failure. Table 6 lists five vulnerability ratings used in New York State. A more detailed description of VR is available in NCHRP Report 590 *(16)*.

Table 6 Vulnerability Ratings used in New York State

Vulnerability Rating	Definition
1	Designates a vulnerability to failure resulting from loads or events that are likely to occur. Remedial work to reduce the vulnerability is an immediate priority
2	Designates a vulnerability to failure resulting from load or events that may occur. Remedial work to reduce the vulnerability is not an immediate priority but may be needed in the near future.
3	Designates a vulnerability to failure resulting from load or events that are possible but not likely. This risk can be tolerated until a normal capital project can be implemented.
4	Designates a vulnerability to failure presenting minimal risk providing that anticipated conditions do not change. Unexpected failure can be avoided during the remaining service life of the bridge by performing normal scheduled inspections, with attention to factors influencing the vulnerability.
5	Designates a vulnerability to failure that is less than or equal to the vulnerability of a structure built to the current design standards. Likelihood of failure is remote.

2.8 Bridge Performance Measures and Project Goals

State Highway Agencies use a variety of performance measures and indices for bridge management decision making. Depending on the goal of the decision, agencies sometimes use more than one index for bridge management. Many measures have been developed for specific business purposes such as eligibility of certain funding programs or criteria for safety thresholds. Table 7 lists the bridge performance measures reviewed in this section as well as other bridge measures and that relate the measures to the goals of bridge projects. The lists of measures and goals are not comprehensive nor are the measures mandatory *(1)*.

Table 7 Bridge Performance Measures by Project Goal

Goal	Performance Measures
Preservation of Bridge Condition	• NBI Rating • Bridge Health Index • Sufficiency Rating
Traffic Safety Enhancement	• Geometric Rating/Functional Obsolescence • Inventory Rating or Operating Rating
Protection from Extreme Events	• Scour Vulnerability Rating • Fatigue/Fracture Criticality Rating • Earthquake Vulnerability Rating • Other Disaster Vulnerability Rating (collision, overload, man-made)

Some bridge performance measures may not be used or well known. One possible reason is that there are few business imperatives among or within agencies to communicate the overall health of their bridge structures. The next section presents the results of a survey of survey of State Highway Agencies to identify the commonly used measurements and how they are use in bridge management decision making.

3 STATE SURVEY ON BRIDGE PERFORMANCE MEASURES

3.1 Survey Purpose and Scope

This section presents the result of a survey to determine the extent to which State Highway Agencies use the BHI for bridge management decision making. The BHI is only one of many bridge performance measures. It has potential utility at both the bridge level and network level. However, there is neither specific business imperative nor guideline for using the BHI for managing bridge assets. The purpose of the survey is to ascertain the experiences and implementation of BHI at highway agencies.

The survey, shown in Appendix C, had two parts. The first part assesses how various bridge performance measures and indexes are currently being used by state agencies for bridge management. The survey participants were asked to indicate the measures or indexes used for bridge projects including preservation, rehabilitation, and replacement projects. The second part specifically focused on the experiences and implementation of the BHI. The survey questions included BHI usage for projects types, for bridge level management, and for network level management. The survey was sent to members of the AASHTO Pontis user Group because the BHI is a feature in the latest version of Pontis. States actively using Pontis are most likely to implement the BHI.

The survey was sent to 87 members of the AASHTO Pontis User Group and 30 responses, representing at least 17 states, were returned (approximately 34.5% return rate). The results shown in Table 8 are evenly split. Half of the respondents indicated they currently use the BHI or a modified BHI for bridge management. The numbers in the parenthesis are the number of responses from the state agency if more than one response was received.

Table 8 Use of BHI among Survey Respondents

BHI Usage	State Participants
Users	(15 Responses) Arizona, Colorado, Iowa, Nevada, New Hampshire, Pennsylvania, Alaska, Texas, Anonymous (7)
Non-Users	(15 Responses) Delaware, Florida, Hawaii, Kansas (2), Massachusetts (2), Montana, Oregon, Utah (2), Wyoming, Anonymous (3)

3.2 Use of Bridge Management Performance Measures

Survey questions asked about the use of various bridge performance measures for any aspect of bridge management decision-making. Twenty-nine participants responded to this question. Figure 1 shows the distribution of the results. Four indexes are dominantly used and they are NBI rating, structural deficiency classification, sufficiency rating, and load rating. Over 80% of the participants use these measures for bridge management. A possible reason is that these measures have associated business imperatives, e.g., the Federal government uses sufficiency rating in distributing funds for the Highway Bridge Program (HBP). Though BHI is not one of dominant indexes, about 41% of respondents reported that they are currently using BHI.

In the “others” category, Montana DOT is developing a modified BHI including smart flag. Wyoming is developing a BHI. State DOTs like Delaware and Texas combining multiple indexes to measure bridge performance. Delaware DOT combines 11 factors (BHI, structural deficiency, load rating, functional obsolete, benefit-cost ratio, scour critical, functional class, detour length, annual average daily traffic (AADT), truck AADT, and historic significance) to evaluate bridge condition and to select the right treatment for their deficient bridges *(17)*.

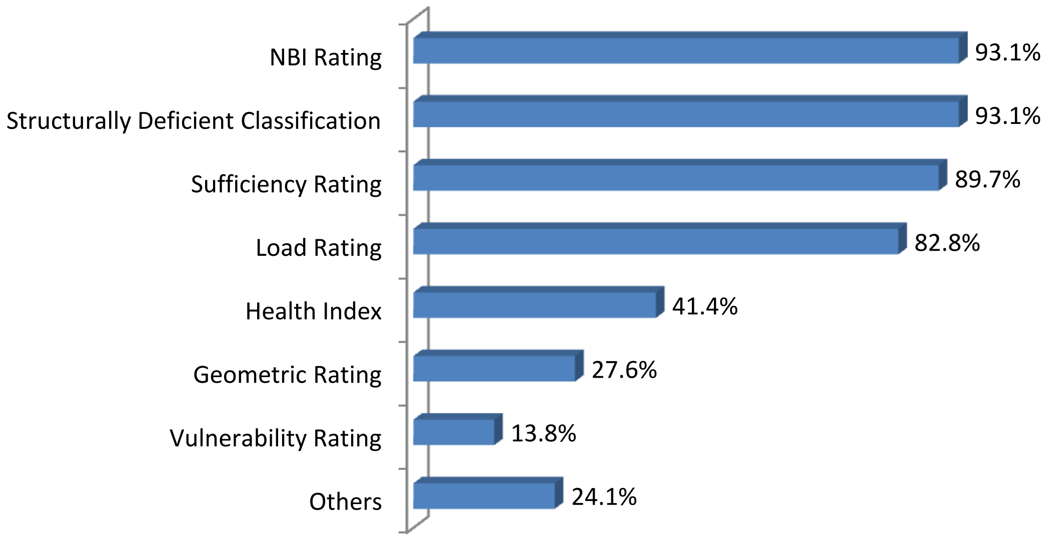


Figure 1 Performance Measures for Bridge Management (29 participants)

3.3 Performance Measures for Project-Level Decision-Making

The survey asked the respondents to indicate the bridge performance measures they use for decision-making on various bridge projects. This question relates the bridge performance measures specifically to project types. The question used broad project types of preservation, rehabilitation or replacement, and improvement. The participants were able to choose more than one measure for each project type. Figure 2 shows the measures for various project types and the percentages based on the 27 participants who responded to this question.

As shown, the State agencies are more likely to use performance measures for decision-making on rehabilitation, replacement and improvement projects than on preservation maintenance projects. Again, guidelines on eligibility for Federal aid on rehabilitation, replacement and improvement projects refer to specific performance measures.

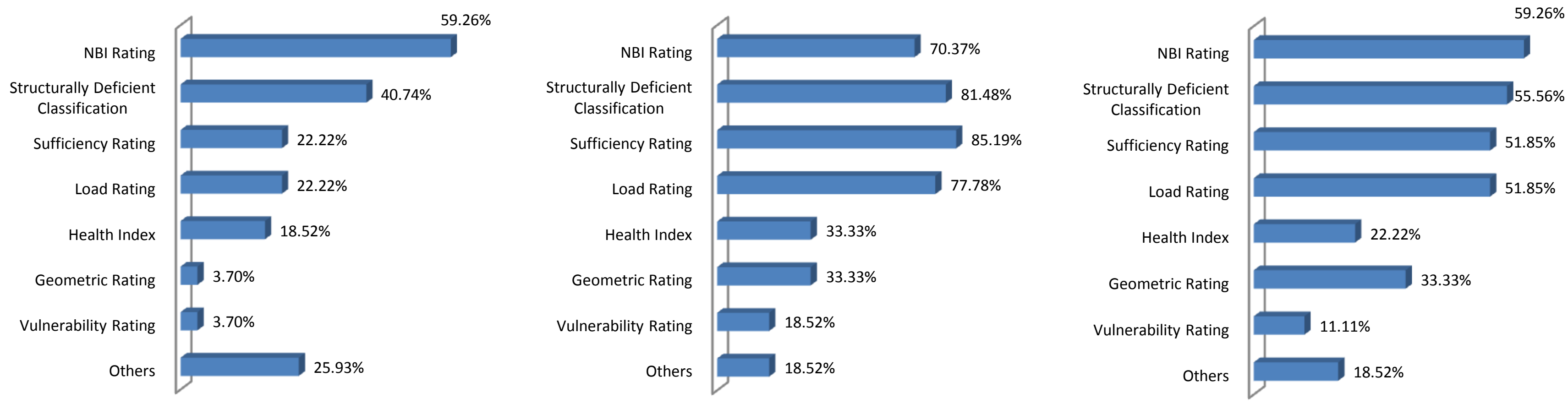
According to the survey results, the NBI rating and structurally deficient classification are the most frequently used indexes for preservation maintenance projects. State DOTs have different approaches for identifying preservation maintenance projects and there is a wide range of treatments *(18)*. About 60% (16 of 27) of the participants reported using the NBI rating for preservation maintenance projects. (The survey did not collect details on how states define preservation maintenance.) The BHI is not commonly used for preservation maintenance projects. Only 19% (5 of 27) of the participants use the BHI for preservation maintenance projects.

Four measures are commonly used for rehabilitation or replacement projects: sufficiency rating, structurally deficient classification, load rating and NBI rating. Notably, more than 85% (23 of 27) of the participants use the sufficiency rating for rehabilitation and replacement projects. Again, sufficiency rating is one of the key performance measures for determining the eligibility for Federal aid. The same four performance measures are also frequently used for improvement projects by more than 51% (14 of 27) of the participants. Only about 33% (9 of 27) and 22% (6 of 27) of the participants use the BHI for bridge rehabilitation or replacement, and functional improvement projects, respectively.

3.4 Use of the BHI for Bridge Management Decision-Making

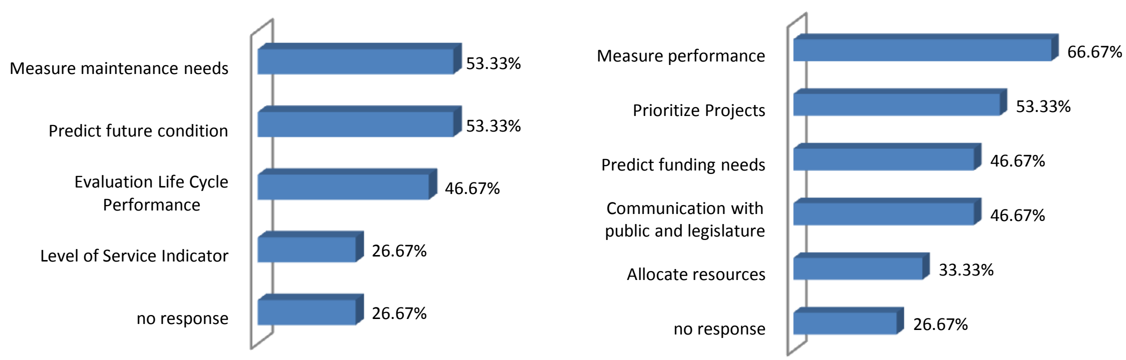
The fifteen participants who use the BHI for their bridge management system were asked about how the BHI is used for bridge level and network level decision making. The results are shown in Figure 3. For the bridge level, more than 53% (8 of 15) of the participants use the BHI for measuring maintenance needs as well as for predicting the future condition. BHI is also frequently used for evaluating the bridge life cycle performance. However, BHI is not commonly used as a level of service (LOS) indicator.

The survey results also show BHI is commonly applied for network level decision-making. The BHI is used as an indicator for measuring network level performance (10 of 15), for prioritizing bridge projects (8 of 15), for predicting funding needs (7 of 15), and for communicating with the public and legislature (7 of 15). BHI is also used for allocating resources.



Preservation Maintenance (47 responses) Rehabilitation or Replacement (87 responses) Improvement (69 responses)

Figure 2 Use of Performance Measures by Project Type (27 participants)



Bridge Level Management Network Level Management

Figure 3 Use of BHI for Bridge Management Decisions (15 participants)

4 BRIDGES AND FAILURE COSTS FOR THE SENSITIVITY ANALYSIS

This section describes the data for the sensitivity analysis. The data sets for calculating the BHI are the element level inspection records and the element weight factors. Bridges of two different material types were investigated. The research team acquired two sets of element failure cost for the analysis: one from Florida DOT and the other from the AASHTO Transportation Asset Management Today website *(5)*. After evaluating the sets of element failure costs, the set from the AASHTO website was used.

4.1 Bridge Element Inspection Data

The analysis focused on 221 bridges in WisDOT District 1 (now part of the agency's Southwest Region) grouped by simple and continuous span prestressed concrete girders. The bridges are located in nine Wisconsin counties: Columbia, Dane, Dodge, Grant, Green, Iowa, Jefferson, Lafayette, Rock, and Sauk. The bridges are located on rural highways except for those in the City of Madison in Dane County. Bridge inspection records for 1996 to 2006 were obtained from the WisDOT.

Table 9 summarizes the bridge inventory information for the analysis. Sixty five of the bridges have simple span prestressed concrete girders and 156 have continuous span prestressed concrete girders. WisDOT has tracked bridge element condition since 1996. The condition of each element are inspected and stored as described in the AASHTO Guide for Commonly Recognized (CoRe) Structural Element *(7)*. The research team got permission to access the bridge management database available in the WisDOT extranet. The available inspection records for were 432 for bridges with simple spans and 1,169 for bridges with continuous spans. Figure 4 shows an example of the bridge inspection records obtained from the WisDOT network.

Table 9 Characterization of Wisconsin Bridges used in the Sensitivity Analysis

Bridge Type Prestressed Concrete Girders	Bridges	Inspection period	Inspection records	Average inspections per bridge
Simple Span	65	1996 – 2006	432	6.6
Continuous Span	156	1996 – 2006	1,169	7.5

4.2 Weighting Factor Data (Failure Cost or Weight Factors)

WisDOT does not have weight factors for its bridge elements. For this study, the research team obtained two alternative sets of the failure costs.

The research team got permission to use Florida's element failure costs for this study from the Florida DOT. The failure cost is the sum of agency cost and user cost *(19)* that were estimated by separate studies *(20, 21)*. The element failure costs for Florida's bridges are available on the consultant's website[4]. Another set of element failure costs, developed for the FHWA, are available on the Transportation Asset Management Today website[5].

[4] http://www.pdth.com/florida.htm

[5] http://assetmanagement.transportation.org/tam/aashto.nsf/docs/E5D2A9F05323691185256B3A004E0632?opendocument&CurrentCategory=c.%20Management%20Systems

Element Inspection (X) Check Elements Inspected					Quantity in Condition States				
Ck	Elem./Env.	Description	Unit	Total QTY.	1	2	3	4	5
X	26 / 4	Conc Deck/Coatd Bars	SF	7031	7031				
X	107 / 2	Paint Stl Opn Girder	LF	1282		1282			
	8 Girdres, painted September 91. Top coat peeling off inside girders bottom flange (bad, almost all gone), prime coat looks good and no rust at this time. Freckled rust starting were paint is gone.								
X	172 / 2	Painted Steel Diaphr	EA	70	25	25	20		
	Top coat peel off, prime coat good condition at this time.								
X	210 / 3	R/Conc Pier Wall	LF	121	121				
X	215 / 3	R/Conc Abutment	LF	84	33	42	9		
	Couple hairline vertical cracks. Spalling in both abutments.- exposed rebar.								
X	234 / 4	R/Conc Cap	LF	78	78				
X	300 / 4	Strip Seal Exp Joint	LF	85	85				
	Clean asap.								
X	311 / 4	Moveable Bearing	EA	16	10	6			
	Top coat of paint peeling off. Exterior bearings are showing moderate rusting.								
X	313 / 4	Fixed Bearing	EA	16	12	4			
	Top coat of paint peeling off. Rusting at exterior bearings								
X	321 / 4	R/Conc Approach Slab	EA	2	1	1			
	Plow damage N. end block - approach a little low.								
X	331 / 4	Conc Bridge Railing	LF	366	216	150			
	Few hairline vertical cracks. North rail has some bad scaling.								
X	342 / 2	RipRap Slope Protect	EA	2	2				
X	357 / 4	Pack Rust Smart Flag	EA	1	1				
	At exterior bearings from leakingthrough strip seal.								
X	358 / 4	Deck Cracking SmFlag	EA	1	1				
	Couple light transvers cracks.								

Figure 4 Example Element Inspection Record at WisDOT (B130052 inspected 2008)

Table 10 lists the elements that comprise the 221 bridges to be analyzed along with a tally of whether a failure cost for the element is available in the Florida DOT and FHWA datasets. Forty six elements are commonly used for the selected WisDOT bridges: 6 deck or slab elements, 18 superstructure elements, 12 substructure elements, 5 smart flags and 5 other elements. Here, “others” elements not categorized as deck, superstructure, substructure or smart flags. The bridges include 15 non-Core elements. Neither the Florida DOT nor the FHWA datasets have failure cost estimates for non-CoRe elements and smart flags. Since the non-CoRe elements are unique for Wisconsin bridges, estimates of their failure costs are not available. Moreover, since smart flags are not elements, they do not have associated weights and failure costs.

The FHWA estimates of failure cost were used for the analysis of Wisconsin bridges because most of the element failure costs are available in the dataset. The FHWA estimate are the minimum element failure costs found by combining minimum long-term costs in each condition state multiplied by transition probabilities and the discount rate.

Table 10 Accounting of Available Element Failure Costs for the Sensitivity Analysis

WisDOT Bridge Element	Element FC		Element Description	Component
	Florida DOT	AASHTO website		
13	Yes	Yes	Concrete Deck, Unprotected with AC Overlay	Deck/Slab
14	No	Yes	Concrete Deck, Protected with AC Overlay	Deck/Slab
22	No	Yes	Concrete Deck, Protected with Rigid Overlay	Deck/Slab
26	No	Yes	Concrete Deck, Protected with Coated Bars	Deck/Slab
40	No	Yes	Concrete Slab, Protected with AC Overlay	Deck/Slab
52	No	Yes	Concrete Slab, Protected with Coated Bars	Deck/Slab
107	Yes	Yes	Painted Steel, Open Girder/Beam	Superstructure
109	Yes	Yes	Prestressed Concrete, Open Girder/Beam	Superstructure
171	No	No	Non CoRe-Unpainted Steel Diaphragm	Superstructure
172	No	No	Non CoRe-Painted Steel Diaphragm	Superstructure
202	Yes	Yes	Steel Painted, Column or Pile Extension	Substructure
205	Yes	Yes	Reinforced Concrete, Column or Pile Extension	Substructure
210	Yes	Yes	Reinforced Concrete, Pier Wall	Substructure
215	Yes	Yes	Reinforced Concrete, Abutment	Substructure
220	Yes	Yes	Reinforced Concrete Submerged Pile Cap/Footing	Substructure
234	Yes	Yes	Reinforced Concrete, Pier Cap	Substructure
250	No	No	Non CoRe-Concrete Diaphragm	Substructure
300	Yes	Yes	Strip Seal Expansion Joint	Superstructure
301	Yes	Yes	Pourable Joint Seal	Superstructure
302	Yes	Yes	Compression Joint Seal	Superstructure
305	No	No	Non CoRe-Elastomeric Expansion	Superstructure
310	Yes	Yes	Elastomeric Bearing	Superstructure
311	Yes	Yes	Movable Bearing	Superstructure
312	Yes	Yes	Enclosed/Concealed Bearing	Superstructure
313	Yes	Yes	Fixed Bearing	Superstructure
321	Yes	Yes	Reinforced Concrete, Approach Slab (w or w/o overlay)	Superstructure
322	No	No	Non CoRe-Bituminous Approach	Superstructure
330	Yes	Yes	Metal Coated, Bridge Railing	Superstructure
331	Yes	Yes	Reinforced Concrete, Bridge Railing	Superstructure
333	Yes	Yes	Others, Bridge Railing	Superstructure
334	Yes	Yes	Metal Uncoated, Bridge Railing	Superstructure
340	No	No	Non CoRe-Concrete Slope Protection	Substructure
341	No	No	Non CoRe-Asphaltic Slope Protection	Substructure
342	No	No	Non CoRe-RipRap Slope Protection	Substructure
343	No	No	Non CoRe-Crushed Aggregate Slope	Substructure
344	No	No	Non CoRe-Bare Slope	Substructure
357	No	No	Pack Rust	Smart Flag
358	No	No	Deck Cracking	Smart Flag
359	No	No	Soffit (undersurface) of Concrete Deck or Slab	Smart Flag
361	No	No	Scour	Smart Flag
362	No	No	Traffic Impact	Smart Flag
400	No	No	Non CoRe-Concrete Wingwall	Other
405	No	No	Non CoRe-Drainage	Other
410	No	No	Non CoRe-Curb	Other
415	No	No	Non CoRe-Sidewalk/Median	Other
416	No	No	Non CoRe-Utilities	Other

5 SENSITIVITY OF HEALTH INDEX TO ELEMENT FAILURE COST

5.1 Analysis Methodology

The sensitivity analysis shows the feasible range of the BHI for various element failure costs. The feasible ranges of the BHI were plotted against the deterministic BHI. The analysis used element failure costs from the AASHTO Transportation Asset Management Today website *(5)* and element level inspection data from WisDOT. To isolate the results from the impacts of variations in the elements' conditions, the conditions were fixed for this analysis.

The steps for the sensitivity analysis are described through a detailed example using bridge B130227. The sensitivity analysis was based on truncated triangular distributions for element failure cost on the ranges of ±10%, ±20%, and ±50% of the FHWA estimates. These distribution ranges were selected because the actual error ranges for failure cost are unknown. For each distribution, 1,000 randomly selected values of FC were used to estimate the distribution of the BHI. The simulation analysis used the commercial @Risk software.

Step 1: *Calculate the deterministic BHI of each inspection.* The deterministic BHI can be computed by the given element failure costs and with bridge condition data as shown in Table 11. Bridge B130227 has eight CoRe elements. The third column shows the given element FCs per unit and columns four through eight present the quantities in each condition state, with the total quantity of each element in the last column. From the given element FCs and the condition, the deterministic BHI (91.17) is calculated following Equations 1, 2 and 3 in section 2 of this report.

Because BHI can be calculated for each inspection, there are 432 deterministic BHIs for the bridges with simple span prestressed concrete girders and 1,169 deterministic BHIs for the bridges with continuous span prestressed concrete girders.

Table 11 Element Condition of B130227 inspected in 1996

Element	Description	Element FC ($/unit)	Quantity in Condition State 1	2	3	4	5	Total Quantity
26	Concrete Deck / Coated Bars	154	0	7653	0	0	0	7653
109	P/S Concrete Open Girder	1,246	1046	0	0	0	0	1046
205	R/Concrete Column	8,593	3	0	0	0	0	3
215	R/Concrete Abutment	3,395	121	3	0	0	0	124
234	R/Concrete Cap	2,415	42	0	0	0	0	42
312	Enclosed Bearing	6,488	24	0	0	0	0	24
321	R/Concrete Approach Slab	23,169	2	0	0	0	0	2
331	Concrete Bridge Railing	364	396	0	0	0	0	396
					Deterministic BHI			91.17

Step 2: *Generate the random estimates of the elements' failure cost.* The failure cost for each element is randomly selected from the triangle distributions within a pre-determined percentage of the given element failure cost. This study used three different ranges, ±10%, ±20% and ±50%, of the failure costs. Because random selections were performed 1,000 times for each element in each range, the simulation process generated 3,000 failure costs for each element. For example, for Element 26 (concrete deck) there were 1,000 failure costs samples between 138.3 and 169.65

(±10%), another 1,000 samples between 123.38 and 185.08 (±20%), and another 1,000 samples between 77.12 and 231.35 (±50%). The deterministic failure cost for Element 26 is $154.23.

<u>Step 3:</u> *Calculate the Bridge Health Index for each simulation run then plot histograms of BHIs.* Because 1,000 different elements failure costs are generated within each range, 1,000 different BHIs are obtained for each. BHIs were computed using the formulas in Equations 1, 2 and 3.

The histograms of the BHIs show the distribution of the BHIs for each range of failure cost estimates. The histograms illustrate the feasible range of the BHI for each estimated range of the failure cost. For comparison, the histograms from each different range of failure cost can be plotted on the same graph.

Figure 5 shows the histograms of BHI for three ranges of uncertainty in the element failure costs. The plot is for a single bridge and inspection record, B130227 inspected in 1996. BHIs generated by ±50% failure costs lead to a wider distribution, while BHIs ±10% built the narrower distribution. The comparison of the histograms illustrates how the feasible range of the BHI increases with the uncertainty in the failure cost. Because there are 432 inspection records for the bridges with simple spans and 1,169 for the bridges with continuous spans, the research produced 1,296 (432*3) histograms for bridges with simple span prestressed concrete girders and 3,507 (1,169*3) histograms for bridges with continuous span prestressed concrete girders.

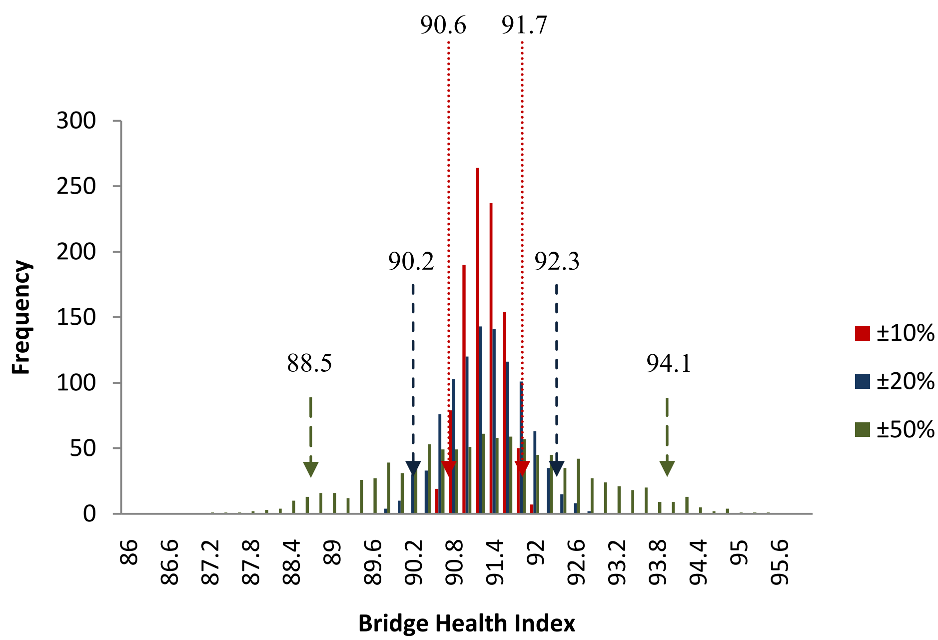


Figure 5 Histograms of BHI for Ranges of Element Failure Costs
(B130227 Inspected 1996, deterministic BHI=91.17)

<u>Step 4:</u> *Calculate the lower and the upper limits of BHI and then plot them with the deterministic BHI.* To show the width of the distribution effectively, the upper and lower limits of BHI are identified such that 95% of the simulated BHIs are within the range. For the bridge, B130227 inspected in 1996, 88.5 and 94.1 are the lower and upper limits of the BHI for failure cost within the range ±50% of the deterministic value. The lower and upper limits of ±20% and ±10% distribution are also shown in Figure 5. Because the distributions are symmetrical, the mean values of three distributions are the same as the deterministic BHI.

Step 5: *Develop the trend models for the upper and lower limits*. From the simulation, it can be concluded that the BHI of bridge B130227 will be within 90.6 and 91.7, within 90.2 and 92.3, and within 88.5 and 94.1 if the element failure costs are within 10%, 20% and 50% of the deterministic values. The deterministic BHI is 91.17.

The analysis found the three pairs of limits for each inspection record. The upper and lower limits were plotted along with the deterministic BHI. After plotting, regression models were developed for the upper and lower limits of the BHI for each of the bridges groups. The models display the feasible range of the BHI for each range of uncertainty in the element failure costs.

5.2 Result of the Sensitivity Analysis

The results of the sensitivity analysis of BHI to variations in element failure cost are shown in Figure 6 and Figure 7 for the bridges with simple and continuous spans, respectively. The results lead to the following observations:

1) *The BHI is more sensitive to change in element failure cost when the deterministic BHI is low.* If the BHI is low there is more uncertainty in the value of the BHI. This tendency can be found regardless of the range of error in element failure cost. Connections of upper and lower limits depict the cone-shaped lines. The lower the BHIs are, the longer the distance between upper and lower limits (Table 12). The distances get wider as the conditions of the bridges worsen.

Table 12 Range of BHI given Estimates of Element Failure Costs

Bridge Type Prestressed Concrete Girders	Failure Cost Estimate	Distance (% change of deterministic BHI) 85	90	95
Simple Span	±10%	1.4 (1.6%)	0.9 (1.0%)	0.5 (0.5%)
	±20%	2.7 (3.2%)	1.8 (2.0%)	0.9 (1.0%)
	±50%	**5.9 (7.0%)**	**4.0 (4.4%)**	**2.0 (2.1%)**
Continuous Span	±10%	1.5 (1.8%)	1.0 (1.1%)	0.5 (0.5%)
	±20%	3.0 (3.6%)	2.0 (2.3%)	1.0 (1.1%)
	±50%	7.7 (9.1%)	5.2 (5.7%)	2.6 (2.8%)

2) *The feasible ranges of BHI are relatively narrower than the range of element FCs estimates.* Table 12 also indicates that the BHI does not change much compared to the change of the element failure costs. For example, by changing the failure costs ±50%, the ranges of the BHIs are 5.9, 4.0, and 2.0 for deterministic BHIs 85, 90, and 95, respectively (bold in Table 12). The ranges are within 7%, 4.4% and 2.1% of the deterministic health index for bridges with simple span prestressed concrete girders.

3) *The feasible ranges of BHI are sensitive to the element failure cost estimates.* A 10% error in the element failure costs causes a comparatively narrow feasible range of the BHI, while a 50% error causes a much wider feasible range for the BHI. The uncertainty of BHI due to a large error in the element failure costs is larger than the uncertainty due to a smaller error in the element failure cost.

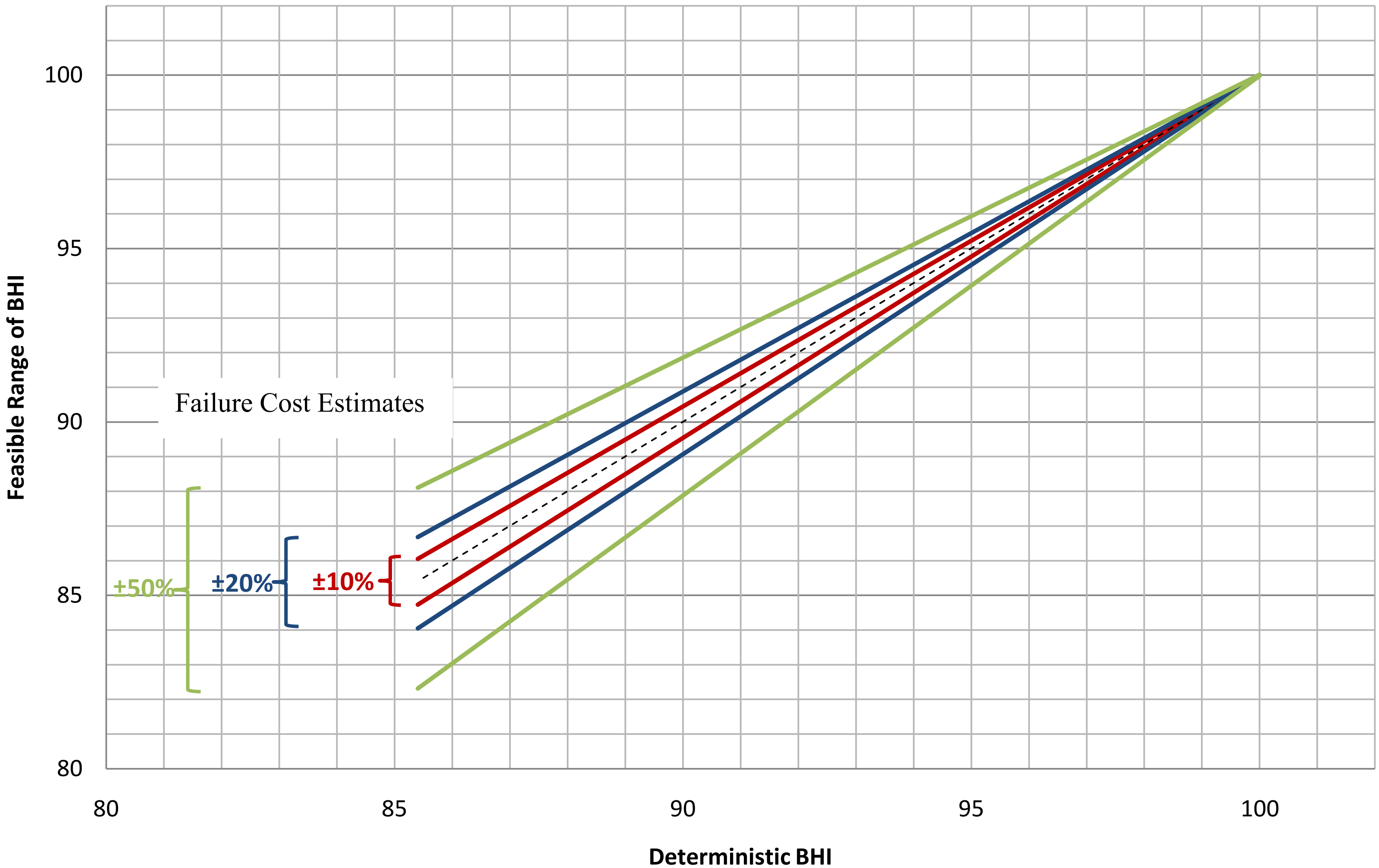


Figure 6 Sensitivity of BHI to Failure Cost: Bridges with Simple Span Prestressed Concrete Girders. (432 inspection records for 65 bridges in Wisconsin)

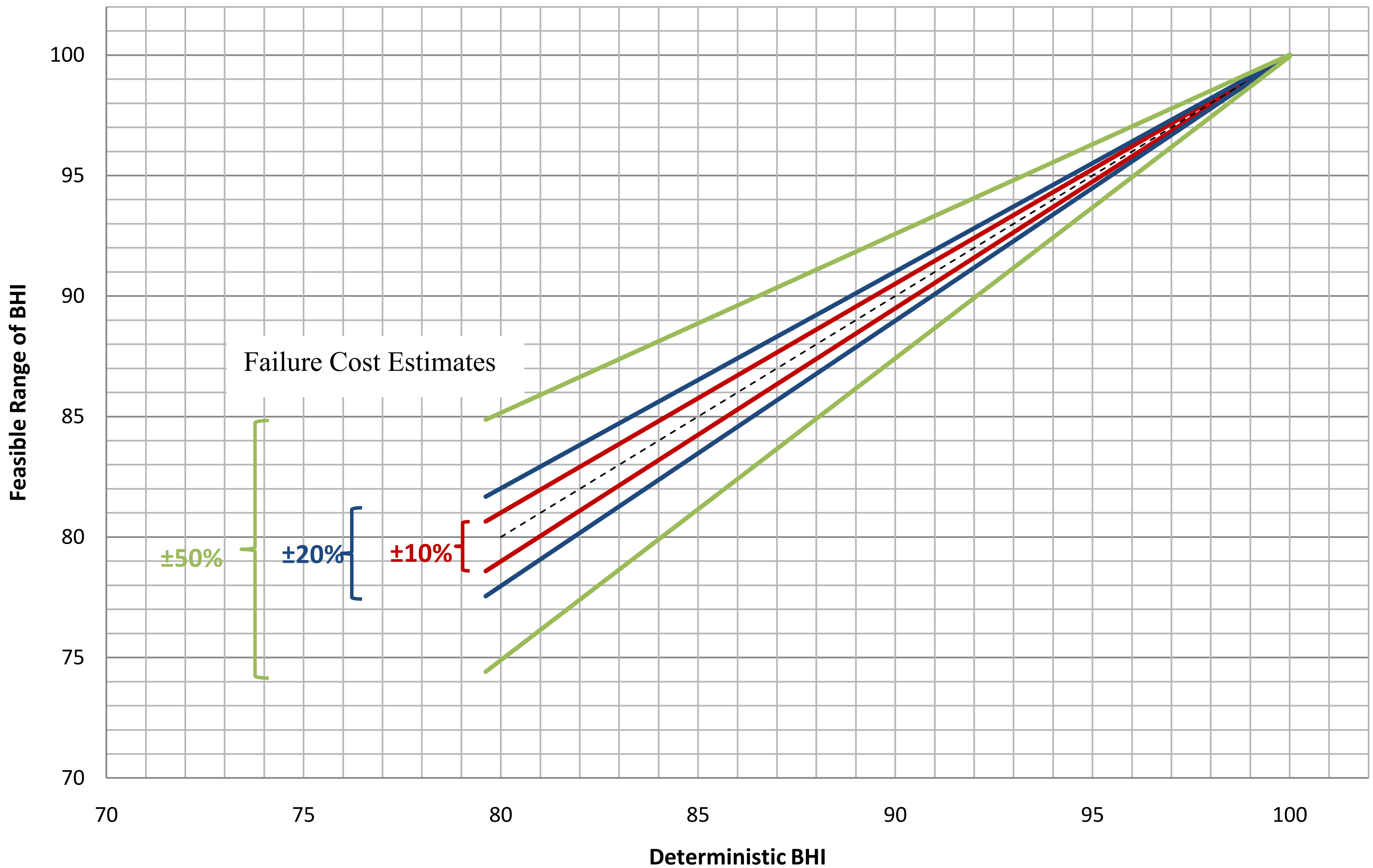


Figure 7 Sensitivity of BHI to Failure Cost: Bridges with Continuous Span Prestressed Concrete Girders (1,169 inspection records for 156 bridges in Wisconsin)

4) *Both upper and lower bounds of the BHI estimates are linear.* Table 13 shows the regression models developed by upper and lower limits of the BHI for each type of bridges. In the model equations, x represents the deterministic BHI and y is the estimated upper and lower limits of BHI due to uncertainty in the failure cost estimate. All R-square values are greater than 0.99. These linear characteristics allow State agencies to anticipate the feasible range of the BHIs by various element failure cost estimates.

Table 13 Regression Models for BHI given Estimates of Element Failure Cost

Bridge Type Prestressed Concrete Girders	Failure Cost Estimate	Limit	Regression Model	R-square
Simple Span	±10%	Upper	$y = 0.9557x + 4.4335$	0.9999
		Lower	$y = 1.0457x - 4.5723$	0.9999
	±20%	Upper	$y = 0.9131x + 8.6977$	0.9997
		Lower	$y = 1.0921x - 9.2182$	0.9997
	±50%	Upper	$y = 0.8155x + 18.459$	0.9905
		Lower	$y = 1.2101x - 21.026$	0.9940
Continuous Span	±10%	Upper	$y = 0.9496x + 5.0503$	0.9999
		Lower	$y = 1.05x - 5.0054$	0.9999
	±20%	Upper	$y = 0.8995x + 10.058$	0.9996
		Lower	$y = 1.1009x - 10.102$	0.9997
	±50%	Upper	$y = 0.7428x + 25.729$	0.9967
		Lower	$y = 1.2526x - 25.316$	0.9982

5) *Bridges in good condition have high values of the BHI regardless of the range of the element failure costs.* Various element failure costs affect the slopes of the upper and lower limits. Because the element condition is fixed in this analysis, changing the element failure cost can affect only the slopes of the upper and lower limits. This fact is shown in the cone-shaped graphs in Figure 6 and Figure 7. There is no offset between the trend lines.

6) *The sensitivity trends are not affected by type of bridge material.* The sensitivity plots of BHI for the simple span bridges (Figure 6) are similar to the ones for the continuous span bridges (Figure 7).

6 SENSITIVITY OF HEALTH INDEX TO ELEMENT CONDITION

6.1 Analysis Methodology

The sensitivity analysis shows the feasible range of the BHI for various element conditions. The feasible ranges of BHIs were plotted against the deterministic BHIs that were calculated using the element failure costs from the Transportation Asset Management Today website *(5)* and bridge conditions from WisDOT. To isolate the results from the impacts of variations in the elements' failure costs, the failure costs were fixed for this analysis.

The sensitivity analysis requires a method for distributing the total quantity of each element among the condition states reasonably reflect uncertainty in the data. This process perturbs the quantities in each condition state by a randomly generated amount and the total quantity of elements is equal to the actual total for the bridge. The uncertainty in element condition was modeled by perturbing the element quantity in each condition state within ±10%, ±20%, and ±50% of the amount in the bridge inspection reports. For each distribution, 1,000 randomly selected errors were used to adjust the distribution of element quantities among the condition states. The simulation analysis used the commercial @Risk software.

The process to conduct the sensitivity analysis is described below.

<u>Step 1</u>: *Calculate the deterministic BHI from each bridge inspection using the given element failure costs and bridge condition data.*

<u>Step 2</u>: *Perturb the quantities in each condition state by pre-determined percentages.* The perturbing process is explained as follows.

1) A random error was selected from the ranges of ±10%, ±20%, or ±50%.

2) The quantities in the element condition states were perturbed according to the random error. Negative errors mean the bridge condition would be worse. A percentage of the quantity in each condition state shifts to the next worse condition state. If the error is positive, then the bridge condition would be improved and a percentage of the quantity in each condition state shifts to the next better condition state. The perturbation process is depicted by the examples in Figure 8.

   This approach assures that the bridge condition is perturbed while the quantities in each condition state (CS) are proportionally corrected so that the total quantity of the element is preserved.

3) Repeat 1 and 2 above, 1,000 times for each element by random sampling and make them ready to calculate the BHI.

<u>Step 3</u>: *Calculate the BHI using the perturbed element conditions using the formulas in Equations 1, 2 and 3.* Because the quantity in each element condition state is modified 1,000 times for each range by the process, a total 1,000 different BHIs can be calculated for each bridge for each range. Once all BHIs are calculated, histograms of the BHIs are plotted. The plots show the feasible range of BHI by changing the element conditions within a certain range. For comparison, the histograms for each range or error were plotted on a single graph in Figure 9. Because there are 432 inspection records for the bridges with simple spans and 1,169 for the bridges with continuous spans, the research produced 1,296 (432*3) histograms for bridges with simple span prestressed concrete girders and 3,507 (1,169*3) histograms for

bridges with continuous span prestressed concrete girders.

Example 1.Error = -10%. The bridge condition is worse than recorded in the field.

Original element quantities							Perturbed					
C1	C2	C3	C4	C5	Total	⇨	C1	C2	C3	C4	C5	Total
29	26	9	3	0	67		26.1= 29-2.9	26.3= 26-2.6 +2.9	10.7= 9-0.9 +2.6	3.6= 3-0.3 +0.9	0.3= 0+0.3	67

10% (2.9) 10% (2.6) 10% (0.9) 10% (0.3)

Example 2. Error = +10%. The bridge condition is better than recorded in the field.

Original element quantities							Perturbed					
C1	C2	C3	C4	C5	Total	⇨	C1	C2	C3	C4	C5	Total
29	26	9	3	0	67		31.6= 29+2.6	24.3= 26-2.6 +0.9	8.4= 9-0.9 +0.3	2.7= 3-0.3+0	0= 0-0	67

10% (2.6) 10% (0.9) 10% (0.3) 10% (0)

Figure 8 Perturbation of Element-level Condition States

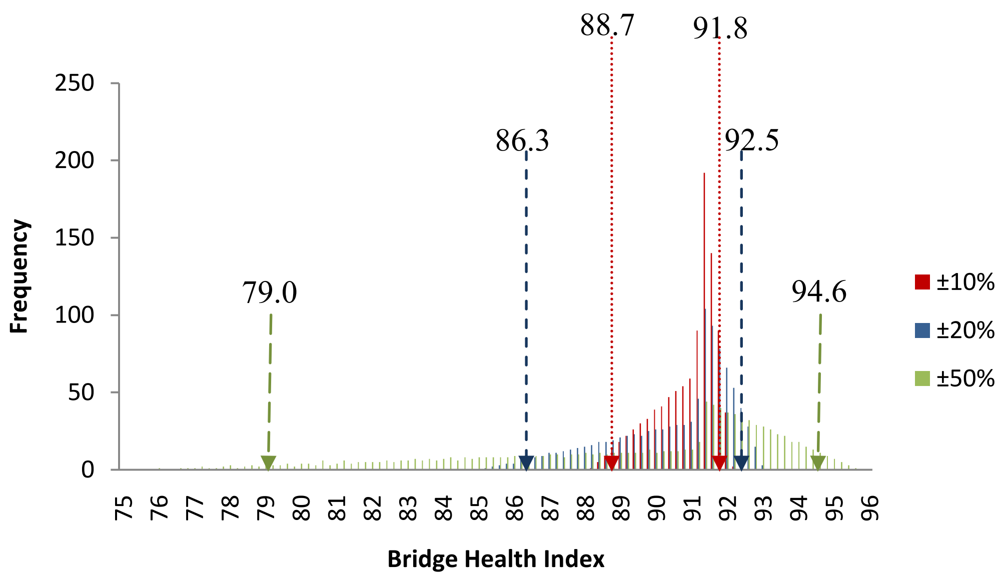


Figure 9 Histogram of BHI for Ranges of Element Condition (B130227 Inspected in 1996, deterministic BHI=91.17)

The comparison of the histograms shows that the feasible range of the BHIs is widest when the bridge condition was highly perturbed. Even though the distribution in the histograms is not symmetrical, BHIs generated by ±50% of the given condition make the wider distribution, while ones by ±10% build the narrower distribution.

<u>Step 4</u>: *Calculate the lower and the upper limits and plot them with the deterministic BHI.*

Calculate the lower and upper limits where 95% of the generated BHIs are within. For B130227 with ±50% change of the element condition, the lower limit is 79.0 while the upper limit is 94.6, as shown in Figure 9. Because the shape of the distribution of the simulated BHIs is not symmetrical, the mean BHI (89.30) is not the same as the deterministic BHI (91.17). Each simulation has three pairs of lower and upper limits and they were plotted with the deterministic BHI. Every bridge inspection has these three pairs of limits in the plot.

Step 5: *Develop the trend models for the upper and lower limits of BHI.* Steps 1 through 4 were repeated for each type of bridge. The analysis found the three pairs of limits for each inspection record. The upper and lower limits were plotted along with the deterministic BHI. After plotting, regression models were developed for the upper and lower limits of the BHI for each of the bridges groups. The models display the feasible range of the BHI for each range of uncertainty in the element conditions.

6.2 Results of the Sensitivity Analysis

The results of sensitivity analysis of BHI to variation in element condition estimates are discussed below. Figure 10 and Figure 11 present the results of the sensitivity analysis for the two bridge groups.

1) *The BHI is sensitive to element condition changes.* The results show that the upper limits of BHIs are fairly sensitive to the condition of the bridges. Longer distances between the upper limits and the deterministic (dashed line) can be observed when the bridges are in bad condition (lower value of BHI). Bridges in bad condition have more uncertainty in the upper limits of BHI. However, the lower limits of BHI are not sensitive to the condition of the bridges as much as the upper limits. The slopes of the lower limits are not significantly different, which means the changes in element condition only offset the lower limits. Table 14 shows the distances between upper and lower limits for various deterministic values of the BHI. The table shows that the distances between the two limits do not appreciably increase as the bridge condition deteriorates.

Table 14 Range of BHI given Estimates in Element Condition

Bridge Type Prestressed Concrete Girders	Element Condition Estimate	Distance (% change of deterministic BHI)			
		85	90	95	100
Simple Span	±10%	3.3 (3.9%)	3.0 (3.4%)	2.7 (2.9%)	2.4 (2.4%)
	±20%	6.7 (7.8%)	6.1 (6.7%)	5.5 (5.8%)	4.9 (4.9%)
	±50%	**16.6 (19.6%)**	**15.2 (16.8%)**	**13.7 (14.4%)**	**12.2 (12.2%)**
Continuous Span	±10%	3.4 (4.0%)	3.1 (3.4%)	2.7 (2.9%)	2.4 (2.4%)
	±20%	6.9 (8.1%)	6.2 (6.9%)	5.5 (5.8%)	4.8 (4.8%)
	±50%	17.2 (20.3%)	15.5 (17.2%)	13.7 (14.4%)	12.0 (12.0%)

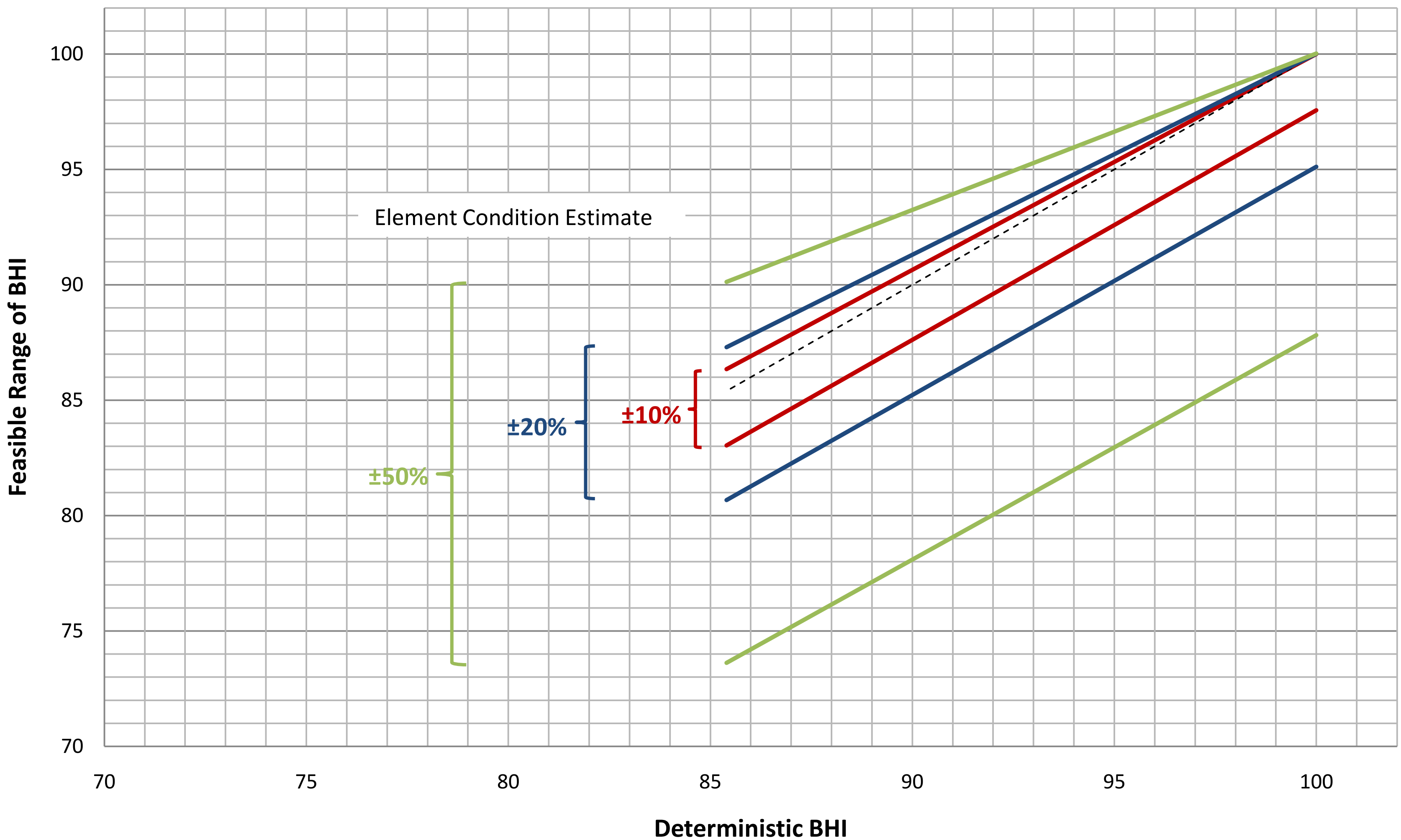


Figure 10 Sensitivity of BHI to Element Condition: Bridges with Simple Span Prestressed Concrete Decks. (432 inspection records for 156 bridges in Wisconsin)

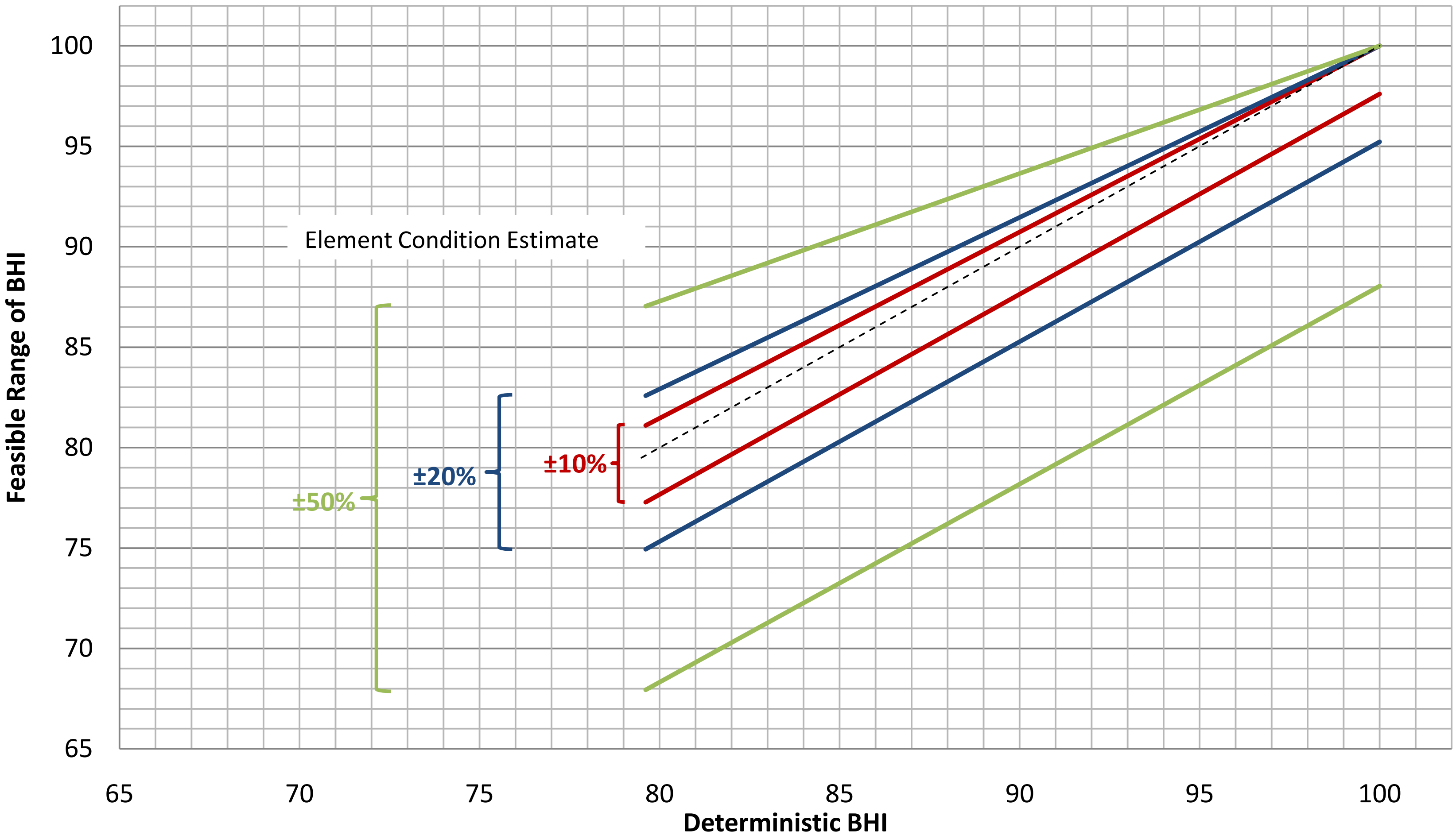


Figure 11 Sensitivity of BHI to Element Condition: Bridges with Continuous Span Prestressed Concrete Decks. (1,169 inspection records for 156 bridges in Wisconsin)

2) *BHI is more sensitive to uncertainty in element condition than to uncertainty in element failure cost.* Comparison of Table 12 to Table 14 illustrates this observation. For example, the ranges of the BHI due to changing failure costs by ±50% are 5.9, 4.0, and 2.0 for deterministic BHI 85, 90, and 95, respectively (Table 12) while the ranges of the BHI due to changing element condition by ±50% are 16.6, 15.2, and 13.7 for deterministic BHIs 85, 90, and 95, respectively (Table 14) in bridges with prestressed concrete deck.

3) *Feasible range of BHI is sensitive to the element condition estimates.* The range developed by ±50% condition estimates is larger than the ranges made by ±20% and ±10%. Table 15 shows the regression models for the upper and lower bound estimates of the BHI for each type of bridges by various ranges of element condition estimates. In the model equations, x is the deterministic BHI and y is the estimated upper and lower limits BHI due to uncertainty in the element condition. The lower limits of the BHI regression models show the sensitivity well. As shown, the slopes of the regression equations for the lower limits models are similar (0.9946 for ±10%, 0.9894 for ±20%, and 0.9728 for ±50% in bridges with simple span prestressed concrete girders) but the offsets reveal the sensitivity. The difference between the intercepts for the ±10% and ±20% models is -1.92 (-3.8219 - (-1.8965)) and between the ±20% and ±50% models is -5.64 (-9.4607 - (-3.8219)). These offsets cause the wider feasible range of BHI as uncertainty in bridge condition increases.

Table 15 Regression Models for BHI given Estimates in Element Condition

Bridge Type Prestressed Concrete Girders	Element Condition Estimate	Limit	Regression Model	R-square
Simple Span	±10%	Upper	$y = 0.9356x + 6.4451$	0.9999
		Lower	$y = 0.9946x$ **- 1.8965**	0.9995
	±20%	Upper	$y = 0.8709x + 12.912$	0.9993
		Lower	$y = 0.9894x$ **- 3.8219**	0.9979
	±50%	Upper	$y = 0.6777x + 32.249$	0.9871
		Lower	$y = 0.9728x$ **- 9.4607**	0.9940
Continuous Span	±10%	Upper	$y = 0.9272x + 7.2783$	0.9999
		Lower	$y = 0.9973x - 2.1186$	0.9993
	±20%	Upper	$y = 0.8546x + 14.545$	0.9993
		Lower	$y = 0.995x - 4.2821$	0.9971
	±50%	Upper	$y = 0.6365x + 36.36$	0.9927
		Lower	$y = 0.9865x - 10.605$	0.9818

4) *Both upper and lower limits are increasing linearly as the deterministic BHI is increasing.* Table 15 shows the linearity of the upper and lower limits with high R-square values.

5) *The type of bridge does not appear to impact the analysis results.* The trend patterns in the sensitivity plots for bridges with simple span prestressed concrete girders (Figure 10) are closely similar to the ones for continuous span bridges (Figure 11).

7 INCORPORATING ELEMENT SMART FLAGS

AASHTO Guide for Commonly Recognized (CoRE) Structure Elements introduced Smart Flags to identify local problems that are not reflected in the CoRe element condition state language *(7)*. Smart Flags can indicate critical defects in a bridge that should be reflected in its BHI. However, because Smart Flags do not have feasible actions associated with them they do not have weights or failure costs. Hence, the research team investigated how to integrate Smart Flags for calculating BHI. This section used rules for applying Smart Flags provided by the Kansas DOT to calculate the BHI of selected bridges in Wisconsin. The resulting BHI with Smart Flags was compared to the computed BHI without consideration of Smart Flags to illustrate the impact of Smart Flags on the BHI.

7.1 BHI Adjustment Rules for Smart Flag in Kansas

The Kansas DOT uses Smart Flags to make adjustments to the BHI. The Smart Flag elements considered in Kansas are deck cracking (358 and 359), fatigue (356), packrust (357), settlement (360) and section loss (363). According to the State bridge engineer at the Kansas DOT, Kansas calculates health indexes of deck, superstructure, substructure, and culvert separately. The health indexes are adjusted according to the policy rules in Appendix D. Table 16 lists the adjustment policy rules for the health index of bridge decks.

Table 16 Rules for Adjusting the BHI for Bridge Deck Smart Flags (Kansas DOT)

Element	Description	Smart Flag Level	Adjustment
358	Cracking on the top surface of concrete deck	1	No adjustment
		2	the maximum deck health index = 95
		3	the maximum deck health index = 85
		4	the maximum deck health index = 70
359	Distressed of the deck soffit (undersurface)	1	No adjustment
		2	No adjustment
		3	the maximum deck health index = 95
		4	the maximum deck health index = 85
		5	the maximum deck health index = 70

7.2 Applying Kansas Smart Flag Rules in Wisconsin

To determine the impact of Smart Flags on the BHI, the adjustment rules used in the Kansas DOT were applied to the Wisconsin bridges in this study. The specific adjustment rules in Table 16 for elements 358 and 359 were applied. As the Kansas DOT recommended, the health index of deck elements were adjusted and then used as input for computing the BHI of the structures. The BHI considering the deck Smart Flags were compared to the corresponding BHI without Smart Flags. Figure 12 presents the comparisons for each of the grouped bridge types.

Because the rules from Kansas constrain the maximum health index of decks, the adjusted BHI of the full structure cannot exceed a certain value. This adjustment generates the offsets on the plots in Figure 12. Applying the deck Smart Flags produced three groups of BHI. One group consists of BHIs with no adjustment, one with maximum deck health indexes of 95 and the others with maximum deck health indexes of 85. There is no bridge where the maximum deck health index should be adjusted to be 70 (Smart Flag level 4 for element 358 and level 5 for element 359). As a result, BHI can be significantly impacted by the deck Smart Flags in the selected bridges in Wisconsin.

Because Smart Flags indicate critical defects which are not expressed in CoRe elements, the Smart Flags cannot improve the BHI. The comparison plots show that the BHI considering deck Smart Flags are the same or lower than ones without deck Smart Flags. For the simple span bridges, the mean BHI considering Smart Flags (98.020) is 0.685 less than the mean BHI without effect of the Smart Flags (98.705). A simple one way t-test indicates the difference in the mean BHI for each bridge group is significant. P-value from the test is enough to be statistically significant. This means the adjusted health index of the deck significantly impacts the BHI of the full structure. The deck Smart Flag also impacts the BHI of the continuous span bridges. The difference of mean BHI is more than 0.4 and that is significant with small p-value (5.329E-39). The detailed results of the one way t-test are listed in Table 17.

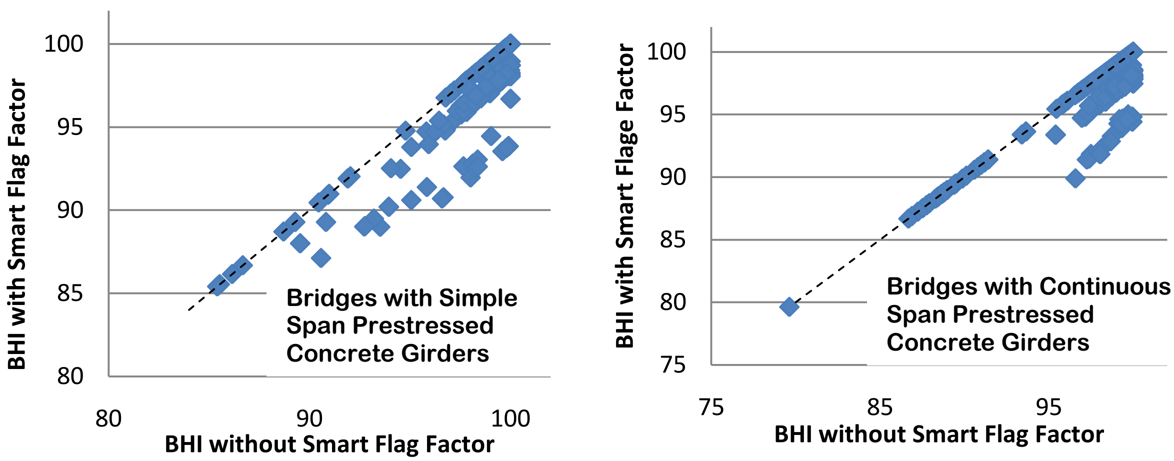


Figure 12 Comparison of BHI with and without Consideration of Smart Flags

Table 17 Statistical Result, One way t-Test: Paired Two Sample for Means

Statistical Parameter	Bridges with Simple Span Prestressed Concrete Girders		Bridges with Continuous Span Prestressed Concrete Girders	
	BHI w/o SF	BHI with SF	BHI w/o SF	BHI with SF
Mean	98.705	98.020	99.057	98.656
Variance	6.185	9.026	4.016	5.130
Hypothesized Mean Difference	0		0	
t Stat	10.916		13.498	
P(T<=t) one-tail	**5.545E-25**		**5.329E-39**	
t Critical one-tail	1.648		1.646	

8 SUMMARY AND RECOMMENDATIONS

A survey of States that use the Pontis Bridge Management System identified the bridge performance measures being used for various bridge project and decision types. More specifically, the survey results are summarized below:

1) The most commonly used bridge performance measures are NBI rating, structurally deficient classification, sufficiency rating and load rating.
2) State DOTs use certain performance measures depending on the type of project. NBI rating is the most common measure for preservation projects; and NBI rating, structurally deficient classification, sufficiency rating and load rating are the most common measures for rehabilitation / reconstruction and improvement projects.
3) The BHI is used for both bridge level and network level decision making. At the bridge level, State DOTs use the BHI to predict a bridge's future condition and measure the preservation needs. At the network level, the BHI is used for measuring network performance and prioritizing projects.

The BHI is relatively new, and there is limited experience among states using it. Some States do not have the sufficient data required to compute the BHI. Most states have the element level inspection records, but not the necessary element weight factors or failure costs.

As a follow-up to the survey, the research team contacted the individual BHI users. Although the BHI is being used for both bridge level and network level decision making, the research team was unable identify neither specific business imperatives nor guidelines for using the BHI in managing bridge assets. There are neither threshold values of the BHI for bridge maintenance, rehabilitation, or replacement actions nor rules for allocating bridge preservation budgets or prioritizing projects according to the health index.

The sensitivity analyses were conducted to investigate how the BHI respond to the variation of two input parameters; the element failure cost and element condition. The analyses used the element failure costs obtained from the AASHTO Transportation Asset Management Today website and bridge element-level conditions from WisDOT.

The BHI is far more sensitive to element condition than to element failure cost. This is good news since bridge condition from element inspection is more deterministic than estimates of element failure costs.

BHI is increasingly sensitive to the element failure costs as bridge conditions worsen. Even small changes in distributions of elements among condition states can significantly affect the BHIs. The larger the element quantities are perturbed, the greater the variation in BHI. This fact verifies that the BHI successfully reflects the bridge condition even though the actual state specific element weight factors are not applied.

For prioritizing among bridges in poor condition, the BHI may not be a robust criterion because small changes in element failure costs could influence the priority order. The study could find out the uncertainty of BHI is increasing linearly as bridge conditions worsen. The BHI is a more robust measure when bridges are in good condition because large variations in element failure cost have little influence on BHI.

The effect of Smart Flags can considerably lower the BHIs. The BHI adjusted Smart Flags for decks are significantly lower than ones not adjusted for Smart Flags. The results of the study are based only on deck Smart Flags. The other components such as superstructures, substructures and culverts can be adjusted as well. The BHI of a structure adjusted by multiple components simultaneously can be affected greatly by Smart Flags.

It is recommended that State DOTs develop rules for the impact of Smart Flags when calculating BHIs. Applying another state's rules such as the Kansas DOT's would be a starting point to reflect Smart Flags. One possible rule is that the failure cost of the deck group is the sum of the failure cost for all deck items multiply by the smart flag condition. This can be repeated with the superstructure and substructure. This may lead more reasonable approach for applying the smart flag. The bridge engineers can determine the amount of the adjustment based on the State environmental circumstances and the importance of the bridge components. Ongoing evaluation of the rules to calculate BHI will ensure that the adjusted BHI can effectively indicate the condition of a structure.

Because there are various ways to estimate element weight factors, comparison of the uncertainty in the BHI when computed using element weights estimated in different ways may be of interest. For example, the study may compare uncertainty in BHI between one scenario where element failure cost is used and another scenario where element replacement cost is used as the element weight.

Recommendations of the research target the potential BHI users.

To the agencies who want to apply BHI for their bridge management system

The BHI is sensitive enough to reflect bridge deterioration that results in small changes in the quantity of elements in each condition state. Since the choice of weight factors can significantly affect the BHI, especially for bridges in bad condition, states should analyze the sensitivity as part of their efforts to develop state-specific weight factors or to adopt weight factors from existing sources.

To the agencies who want to develop the guideline to use BHI

The long term trends in BHIs can give agencies new ways to model or predict deterioration rates and to quantify the impact of various preservation activities. Agencies will need to develop relationships between BHI and the actual bridge condition. With these relationships and investigation of the element condition state, agencies can define threshold levels for bridge preservation and recommend the activities for preventive maintenance, rehabilitation, and reconstruction. Furthermore, knowledge of current condition, deterioration rates, and maintenance threshold in terms of BHI can contribute to development of policies or guidelines for allocating preservation budgets. A combination of BHI and actual condition state data might be used to formulate an agency's work program. Moreover, the use of guidelines requires ongoing evaluation of the BHI to ensure that progress is being made toward achieving the agency's bridge management goals. Agencies should continue to monitor the usage of BHIs and to update their guidelines accordingly.

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Appendix A. List of Acronyms

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
BHI	Bridge Health Index
BMS	Bridge Management System
Caltrans	California Department of Transportation
CoRe	Commonly Recognized
CS	Condition State
DelDOT	Delaware Department of Transportation
DOT	Department of Transportation
FC	Failure Cost
FHWA	Federal Highway Administration
FO	Functionally Obsolete
GAO	Government Accountability Office
HBP	Highway Bridge Program
HBRRP	Highway Bridge Rehabilitation and Replacement Program
LOS	Level of Service
Mn/DOT	Minnesota Department of Transportation
NBI	National Bridge Inventory
NCHRP	National Cooperative Highway Research Program
NYSDOT	New York State Department of Transportation
SAFETEA-LU	Safe Accountable Flexible Efficient Transportation Equity Act: A Legacy for Users
SD	Structurally Deficient
SR	Sufficiency Rating
VR	Vulnerability Rating
WF	Weight Factor
WisDOT	Wisconsin Department of Transportation

Appendix B. AASHTO Commonly Recognized (CoRe) Elements

B.1 Bridge CoRe Element (Decks/Slabs)

Core Element	Unit	Element Number (Decks)	Element Numbers (Slabs)
Concrete (Bare)	EA	12	38
Concrete Unprotected with AC Overlay	EA	13	39
Concrete Protected with AC Overlay	EA	14	40
Concrete Protected with Thin Overlay	EA	18	44
Concrete Protected with Rigid Overlay	EA	22	48
Concrete Protected with Coated Overlay	EA	26	52
Concrete Protected with Cahtodic System	EA	27	53
Steel-Open Grid		28	
Steel-Concrete Filled Grid		29	
Steel-Corrugated/Orthotropic/Etc.		30	
Timber (Bare)		31	54
Timber Protected with AC Overlay		32	55

B.2 Bridge CoRe Element (Superstructure)

CoRe Element	Unit	Steel Unpainted	Steel Painted	P/S Conc	Reinf Conc	Timber	Other
Closed Web/Box Girder	m	101	102	104	105		
Open Girder/Beam	m	106	107	109	110	111	
Stringer (stringer-floor beam system)	m	112	113	115	116	117	
Through Truss (bottom chord)	m	120	121				
Through Truss (excluding bottom chord)	m	125	126				
Deck Truss	m	130	131				
Timber Truss/Arch	m					135	
Arch	m	140	141	143	144		145
Cable (not embedded in concrete)	EA	146*	147**				
Floor Beam	m	151	152	154	155	156	
Pin and Hanger Assembly	EA	160	161				

* Denotes uncoated steel

** Denotes coated steel

B.3 Bridge CoRe Element (Substructure)

CoRe Element	Unit	Steel Unpainted	Steel Painted	P/S Conc	Reinf Conc	Timber	Other
Column or Pile Extension	EA	201	202	204	205	206	
Pier Wall	m				210		211
Abutment	m				215	216	217
Submerged Pile Cap/Footing	EA				220		
Submerged Pile	EA	225		226	227	228	
Pier Cap	m	230	231	233	234	235	
Culvert	m	240			241	242	243

B.4 Bridge CoRe Element (Other Super/Substructure)

CoRe Element	Unit	Metal Coated	R/S Conc	Reinf Conc	Timber	Other	Metal Uncoated
Strip Seal Expansion Joint	m					300	
Pourable Joint Seal	m					301	
Compression Joint Seal	m					302	
Assembly Joint/Seal (modular)	m					303	
Open Expansion Joint	m					304	
Elastomeric Bearing	EA					310	
Movable Bearing (roller, sliding, etc.)	EA					311	
Enclosed/Concealed Bearing	EA					312	
Fixed Bearing	EA					313	
Pot Bearing	EA					314	
Disk Bearing	EA					315	
Approach Slab w/ or w/o AC Overlay	EA		320	321			
Bridge Railing	m	330		331	332	333	334

B.5 Bridge CoRe Element (Smart Flag)

Element#	Unit	Element
356	EA	Steel Fatigue
357	EA	Pack Rust
358	EA	Deck Cracking
359	EA	Soffit(or undersurface) of Concrete Deck or Slab
360	EA	Settlement
361	EA	Scour
362	EA	Traffic Impact
363	EA	Section Loss

Appendix C. Survey

Implementation of Bridge Health Index (HI) for Bridge Management System

Survey of Pontis Users

Conducted by
University of Wisconsin-Madison

The University of Wisconsin-Madison, in conjunction with the Wisconsin Department of Transportation (WisDOT), is conducting a study on using the bridge Health Index (HI). Please help by telling us how your state computes and uses the bridge Health Index. For comparison, we are collecting information about the use of other bridge indexes in decision making.

We appreciate your time and assistance on this project. If you have questions, please contact Professor Teresa M. Adams at (608) 263-3175 or adams@engr.wisc.edu. THANK YOU!

I. Contact Information

1. Name: ________________________
2. State: ________________________
3. Title: ________________________
4. Phone: ________________________
5. Email: ________________________

II. Bridge Performance Measurement Index

1. Which of the following indexes does your state use for bridge management? *Check all that apply.*
   a. ☐ NBI Condition Rating
   b. ☐ Health Index
   c. ☐ Sufficiency Rating
   d. ☐ Geometric Rating
   e. ☐ Load Rating
   f. ☐ Vulnerability Rating
   g. ☐ Structurally Deficient Classification
   h. ☐ Others _________________

2. For which types of projects does your state use the bridge performance measurement indexes? *Check all that apply.*

Project Type	NBI Rating	Health Index	Sufficiency Rating	Geometric Rating	Load Rating	Vulnerability Rating	Structural Deficient Classification
Preventive Maintenance	☐	☐	☐	☐	☐	☐	☐
Rehabilitation/Replace	☐	☐	☐	☐	☐	☐	☐
Improvement	☐	☐	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐	☐	☐
Security	☐	☐	☐	☐	☐	☐	☐

III. Implementation of the Index

1. Does your state use the indexes for bridge management decision making? *Check all that apply.*

Bridge Management Level	Decision Support	NBI Rating	Health Index	Sufficiency Rating	Geometric Rating	Load Rating	Vulnerability Rating	Structurally Deficient Classification	
Bridge Level	Evaluate life cycle performance of maintenance & rehabilitation	☐	☐	☐	☐	☐	☐	☐	
	Level of service indicator	☐	☐	☐	☐	☐	☐	☐	
	Predict future condition / Quantify Remaining Life	☐	☐	☐	☐	☐	☐	☐	
	Measure maintenance needs	☐	☐	☐	☐	☐	☐	☐	
Network Level	Measure Network Performance	☐	☐	☐	☐	☐	☐	☐	
	Allocate Resources	☐	☐	☐	☐	☐	☐	☐	
	Prioritize Projects	☐	☐	☐	☐	☐	☐	☐	
	Predict Funding Needs	☐	☐	☐	☐	☐	☐	☐	
	Communicate with the public and legislature	☐	☐	☐	☐	☐	☐	☐	

2. If your use HI, please indicate the decision criteria.
   - ☐ We are using Pontis default decision making criteria.
   - ☐ Yes, we use our own state-specific criteria. For more information, please contact

     Name: ________________________________

     Phone: ________________________________

     Email: ________________________________

IV. Bridge Health Index

1. If your state uses the bridge Health Index, please tell us how you calculate the HI values.

☐ We use the Pontis default values of Weight Factor (WF) and element replacement cost
☐ We use our own state-specific Weight Factor (WF) and element replacement costs. For more information, please contact
Name: ________________________________
Phone: ________________________________
Email: ________________________________

☐ We use the Pontis default values of Element Failure Costs
☐ We use state-specific Element Failure Costs. For more information, please contact
Name: ________________________________
Phone: ________________________________
Email: ________________________________

☐ We use Smart Flags when calculating bridge Health Index. For more information, please contact
Name: ________________________________
Phone: ________________________________
Email: ________________________________

☐ We include non-CoRe elements when calculating bridge Health Index. For more information, please contact
Name: ________________________________
Phone: ________________________________
Email: ________________________________

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THANK YOU FOR PARTICIPATING IN OUR SURVEY!

Appendix D. Business Rules for Smart Flags in Computing the BHI

These business rules are used by the Kansas DOT for apply the effects of Pontis element Smart Flags when computing the health index of decks, substructures, superstructures and culverts.

Deck Health Index (top, 358, bottom 359)

If the Top Deck Smart Flag = 1, the deck health index is not adjusted.
If the Top Deck Smart Flag = 2, the maximum deck health index = 95.
If the Top Deck Smart Flag = 3, the maximum deck health index = 85.
If the Top Deck Smart Flag = 4, the maximum deck health index = 70.

If the Bottom Deck Smart Flag = 1, the deck health index is not adjusted.
If the Bottom Deck Smart Flag = 2, the deck health index is not adjusted.
If the Bottom Deck Smart Flag = 3, the maximum deck health index = 95.
If the Bottom Deck Smart Flag = 4, the maximum deck health index = 85.
If the Bottom Deck Smart Flag = 5, the maximum deck health index = 70.

Superstructure Health Index (Fatigue, 356, Packrust, 357, Section Loss, 363)

If the Fatigue Smart Flag = 1, the maximum superstructure health index = 95.
If the Fatigue Smart Flag = 2, the maximum superstructure health index = 85.
If the Fatigue Smart Flag = 3, the maximum superstructure health index = 70.

If the Pack Rust Smart Flag = 1, the superstructure health index is not adjusted.
If the Pack Rust Smart Flag = 2, the maximum superstructure health index = 95.
If the Pack Rust Smart Flag = 3, the maximum superstructure health index = 85.
If the Pack Rust Smart Flag = 4, the maximum superstructure health index = 70.

If the Section Loss Smart Flag = 1, the superstructure health index is not adjusted.
If the Section Loss Smart Flag = 2, the maximum superstructure health index =95.
If the Section Loss Smart Flag = 3, the maximum superstructure health index =85.
If the Section Loss Smart Flag = 4, the maximum superstructure health index =70.

Culvert Health Index (360)

If the Settlement Smart Flag = 1, the culvert health index is not adjusted.
If the Settlement Smart Flag = 2, the culvert health index is not adjusted.
If the Settlement Smart Flag = 3, the maximum culvert health index = 80.