A UNIFIED CONDITION INDEX FOR EXISTING CONCRETE BRIDGES IN CANADA

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Introduction

Satisfactory performance of existing civil infrastructure is essential to maintain economic growth and social development of a modern society. As a result, aging civil infrastructure has become a major social and economical concern in North America. The transportation system is one major group of the infrastructure system and includes ground, air, water ways and mass transportation (Hudson et al. 1998). In particular, bridges are important item of this system. Bridges have a distinct function of joining highways as crucial nodes. In addition, bridges are exposed to aggressive environment and increasing traffic volumes and truck loads (Frangopol and Liu 2005).

Deterioration is a major problem in the operation of a nation's highway bridges. Maintenance, repair and replacement (MR&R) of deteriorating bridges are among the most expensive items for highway agencies. In addition to agency cost, MR&R decisions have an indirect cost due to bridge closure impact on the users and the economy. Justifying decisions concerning bridge MR&R requires systematic and logical procedures to assess the conditions of existing bridges.

The purpose of this paper is to review bridge condition assessment practice in Canada and to develop a bridge condition assessment methodology. The developed methodology is proposed to unify bridge condition assessment in Canada. Unifying bridge condition assessment is an essential step toward establishing a unified bridge management practice in Canada.

Bridge condition assessment

Bridge conditions are assessed through inspection. Inspection involves the use of various techniques to assess the physical condition of bridges. Bridge inspection procedures and guidelines are documented in well-developed bridge inspection manuals such as Ontario Structure Inspection Manual (OSIM 1989) published by the Ontario Ministry of Transportation and Bridge Inspector's Training Manual 90 (FHWA 1991) published by the U.S. Department of Transportation. These manuals provide the basic guidelines for bridge inspection and condition evaluation.

Bridge condition assessment practice in Canada

Several Canadian Ministries of Transportations were contacted and some were visited to question the current practice in bridge condition assessment. This research pays attention to the need for nationally-unified bridge management practice in Canada. At the bridge condition assessment level, wide discrepancies exist between different Canadian provinces. Few Canadian provinces have a sufficiently well-developed inspection and condition assessment methodologies, while some other provinces have not used any bridge condition index yet.

The Ministry of Transportation of Ontario (MTO) has one of the most advanced bridge management systems in Canada. The bridge office in the MTO led a task force to develop a new performance measure for bridges. The Regional Structural Sections and the Program Management Branch have provided valuable input in the development of Bridge Condition Index. The index is a single-number assessment of the bridge condition based on the remaining economic worth of a bridge. It is based on the premise that a bridge has an initial value and as it deteriorates to a lower condition, its value decreases. The initial value is calculated using unit replacement costs and actual quantities for the various bridge elements.

The department of transportation of Alberta performs condition assessment on existing bridge structures to determine the optimum long term solution for maintenance, rehabilitation or replacement. The objective is to maximize the service life of the structure at a minimum life cycle cost. The assessment is intended to develop a strategy that answers "what, when and how much". The Department identifies bridge structures that may require maintenance, rehabilitation or replacement in a short-term programming period. Structures may be identified for an assessment based on condition and functional deficiencies or proposed highway improvements. In Alberta, an overall bridge index is the average of the index of sub-structure and super-structure. The agency uses a functional rating similar to the sufficiency rating adopted in the United States.

In Quebec, the ministry of transportation uses a rating from 1 to 9 for each bridge elements. This system is similar to the one used by the national bridge inventory in the United States. The ministry of transportation of Quebec is working with Stantec Consulting to review its bridge asset management methodology and intends to create or adopt a system similar to the Ontario Bridge Management System.

Prince Edward Island Transportation and Public Work have a total of 1,300 bridges in their inventory. Bridge visual inspection is completed every 3rd year. Bridges are given an overall rating as a whole. This rating used is 1, 2, 3 for significant work is required, minor work is required, or no work is required, respectively.

Nova Scotia Department of Transportation and Public Works is responsible for the management of approximately 4000 bridges on the provincial highway system in Nova Scotia. They use a condition rating from 1 to 9 similar to the National Bridge Inventory in the United States. Nova Scotia Transportation and Public Work retained Stantec Consulting to implement a customized version of the Ontario Bridge Management System for their province.

Bridge element condition index

Condition assessment starts with visual inspection by an experienced inspector to estimate and record the extent of defects and distress. Visual inspection reveals defects such as cracking, scaling, spaling, delaminations and reinforcement corrosion. Traditional NDT techniques such as hammer sounding and chain drag are performed to quantify the extent of defects observed by the visual inspection.

The OSIM has defined four material condition states to categorize the condition of bridge elements. These condition states are Excellent, Good, Fair and Poor. At any given time, quantities within a bridge element may be in any of these different condition states. The inspector estimates and records the quantities (area, length, or unit) of the bridge elements in each condition state. The general description of the four condition states is presented Table 1.

Table 1. Condition states general description (OSIM).

Condition state	Description	Examples
Excellent	-This refers to a part of an element that is in as constructed condition	-“Bug holes” in concrete barrier walls
Good	-This refers to a part of an element where the first sign of minor defects are visible.	-Light corrosion -Light scaling -Narrow cracks in concrete
Fair	-This refers to a part of an element where medium defects are visible.	-Medium corrosion (up to 10% section loss)
Poor	-This refers to a part of an element where sever and very defects are visible.	-Sever corrosion (greater than 10% section loss) -Spalling, delamination, etc.

In this research, an element level condition index is proposed. The concept is based on the remaining value of a deteriorated bridge elements. Excellent condition bridge element has a value of 100% and this value decreases as the bridge element deteriorates to lower conditions. The four material condition states described in Table 1 are used to categorize the condition of bridge elements. At any given time, quantities within a bridge element may be in any of these different condition states. The bridge inspector is required to estimate the quantities of each condition state for each element.

Based on discussions with bridge engineers, values for element's quantities in each of the four condition states are developed. These values are 100%, 70%, 40%, and 5% for condition states Excellent, Good, Fair and Poor, respectively. During bridge inspection, the inspector estimates the quantities in these condition states for each element. For example, if the inspector reports that 50% of the bridge deck area is in Good condition and 50% is in Poor condition, then 50% of the deck has 70% remaining value and 50% of the deck has 40% remaining value.

Using the remaining value of a deteriorated element principle, the (BECI) is developed. The BECI is a number from 0 to 100 where 100 signifies the best possible condition without distress, descending values represent increased degrees of distress. The BECI is calculated by taking the ratio of the current or deteriorated bridge element value to the initial value as follows:

$$\text{BECI} = (\text{current element value}/\text{initial element value}) \times 100 \qquad (1)$$

where current element value is the summation for quantity in each state multiplied by the value of the element in that state; initial element value is the value of the element at brand new condition.

The BECI is estimated for each bridge element independently. Increased deteriorated quantities of an element reduce the element condition index. The decision maker can retrieve bridge elements from a bridge network that are at a specific condition index and prioritize these elements for action if necessary. The following is an example to demonstrate the concept of BECI. Bridge inspection team inspected 800 m^2 total area bridge deck and reported the results as presented in Table 2.

Table 2. Bridge deck condition inspection results.

Condition state	Area of the deck m^2
Excellent	400
Good	100
Fair	150
Poor	150

Current deck value = (400 × 1.0) + (100 × 0.70) + (150 × 0.40) + (150 × 0.05) = 537.50

The bridge deck condition index can be estimated as the total value of the current value divided by the initial value of the bridge deck as given in Equation 1.

$BECI_{DECK}$ = (537.50 / 800) × 100 = 67

The condition index of the various elements can be estimated as presented above. The overall bridge condition index can be computed by combining the different elements condition indices. The next sections present the proposed methodology to develop a combined bridge condition index.

Overall bridge condition index

The developed bridge elements condition indices are required to be combined to form one index. The combined index is the Bridge Condition Index (BCI) that represents the overall material and structural condition of the bridge. The developed bridge elements condition indices rate the material conditions of the different bridge elements. However, the material condition rating does not influence the element’s overall structural condition rating in a similar degree. Different elements have different structural importance and the same element can have different structural importance based on the degree of damage and distress. Bridge experts can use their experience and knowledge to analyze bridge inspection results and to develop structural importance values specific to the bridge under consideration. To perform this, a systematic and consistent methodology is required. To develop the required methodology, the Analytic Hierarchy Process (AHP) is employed. The developed methodology is presented in the following section.

Structural importance of bridge elements

There is no precise definition for the structural importance of the different bridge elements in the literature. Tee et al. (1988) referred to the structural importance as the structural role of the element; however, this definition is inadequate. In this research, the structural importance of bridge element is defined as the degree the element contributes to the overall structural integrity and safety of the bridge.

The AHP is employed to extract the expert judgment in order to evaluate the structural importance of the different bridge elements. The AHP is a general theory of measurements developed by Thomas Saaty (1980). It provides an effective analytical tool to deal with complex decision making. It is a multi-criteria decision process that utilizes both actual measurements and expert judgment. The AHP has a special concern with departure from consistency and the measurement of this departure. The following is a presentation of the AHP concept and the use of this process in evaluating the structural importance

Two fundamental steps are required to use the AHP methodology. First, a complex system is broken into a hierarchy structure to represent the problem. Second, pairwise comparisons are performed to measure the relative impact of different elements in the hierarchy and to establish relations within the structure. A fundamental scale of absolute values for representing the strength of judgments has been developed and validated (Saaty 1980, Saaty 2001). In this approach the decision maker expresses his/her opinion about the value of one single pairwise comparison at a time. Usually, the decision maker has to choose an answer among discrete choices. Table 3 presents the scale of relative importance.

Table 3: Scale of relative importance (Saaty, 2001).

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

For the purpose of evaluating the structural importance of the bridge elements, a two level hierarchy structure is developed as presented in Figure 1. The bridge experts are required to compare each two elements with respect to the overall bridge structural criticality and to specify the intensity of the relative importance. If an element jeopardize the bridge safety and integrity while another one has limited effect on safety and integrity then the first one has absolute importance over the second one.

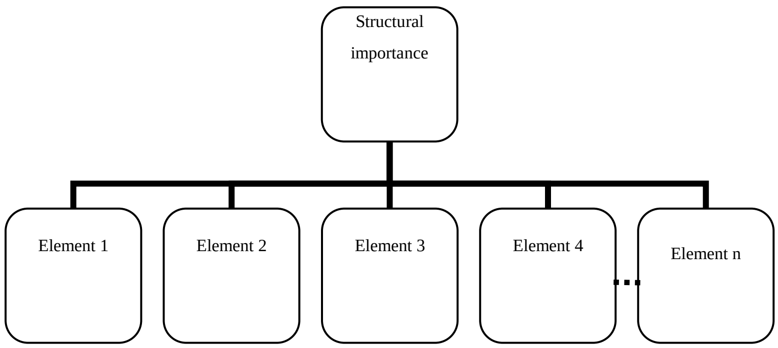

Figure 1. Hierarch structure for the elements' structural importance.

This process requires through understanding of the structural behavior and the structural role of the various bridge elements. In addition, defects and extent of distress of the various elements determine their structural importance. The detailed visual inspection should capture these defects and evaluate the extent of distress of the various elements. The effect of these defects and distress on the structural performance of the elements should be analyzed and included in the comparisons. The results of the pairwise comparison are laid in a reciprocal matrix referred to as the matrix of comparison as shown in Table 4. In this matrix, S_{ij} is the relative structural importance of element i with respect to j. This matrix is reciprocal once it satisfies the following two conditions: $S_{ij} = 1/S_{ji}$ and $S_{ii} = 1$ for all i and j.

The structural importance of the various elements is developed as a vector of priorities. The vector of priorities is a normalized eigenvector and estimated in two steps. First, normalize the developed matrix of comparison by computing the sum of each column, and then divide each element in each column by the sum of that column. Second, compute the average of each row. The average value of each row represents the priority weight of the corresponding element. First row corresponds to the first element and second row corresponds to the second element and so on.

Table 4. Pairwise comparison of structural importance of the various bridge elements.

	Elem. 1	Elem. 2	Elem. 3	Elem. 4	……	Elem. N
Elem. 1	1	S_{12}	S_{13}	S_{14}	……	S_{1n}
Elem. 2	S_{21}	1	S_{23}	S_{24}	……	S_{2n}
Elem. 3	S_{31}	S_{32}	1	S_{34}	……	S_{3n}
Elem. 4	S_{41}	S_{42}	S_{43}	1	……	S_{4n}
. .	. .	. .	. .	. .	. .	. .
Elem. N	S_{n1}	S_{n2}	S_{n3}	S_{n4}	……	1

One feature of the AHP methodology is checking for consistency. The process allows inconsistency in the pairwise comparisons to a certain extent. If all the comparisons are perfectly consistent, then $S_{ij} = S_{ik} \times S_{kj}$ should always be true for any combination of comparisons taken from the matrix of comparison.

A consistency index (CI) can be determined for this purpose. Small value of the CI represents small deviation from consistency which reflects an acceptable consistent judgment.

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (2)$$

where λ_{max} is an approximation of maximum eigenvalue. A simple way to obtain λ_{max} is by adding the elements in each column in the matrix of comparison and multiplying the resulting vector by the vector of priorities (i.e. the approximated eigenvector) obtained earlier.

In AHP, the pairwise comparisons are considered to be adequately consistent if the corresponding consistency ratio (CR) is less than 10% (Saaty, 1980). CR is calculated as CI/RI where RI is a random consistency index derived from a large sample of randomly generated reciprocal matrices. A consistency ratio less than 10% reflects an informed judgment that could be attributed to expert knowledge about the problem under study. If this limit is not achieved, the expert is required to revise the pairwise comparisons to improve consistency.

Combined bridge condition index

To obtain the bridge condition index, the condition rating and the structural importance of the different bridge elements must be combined. The MAUT is used perform this task. One form of the MAUT is the additive utility model. This model is most commonly used in view of its practicality and simplicity. In this model, the overall BCI is expressed in terms of the BECI and the structural importance of each element as follows:

$$BCI = \sum_{i=1}^{n} BECI_i \times S_i \tag{3}$$

where $BECI_i$ is the condition index of element i, S_i is the structural importance of the same element and n is the number of the bridge elements. This model requires that: $S_1 + S_2 + \ldots + S_n = 1$. This condition is satisfied since the eigenvector approach develops weights with a total sum equals to 1.

Case study

In this section, a case study is used to demonstrate the proposed methodology. The case study is based on inspection results extracted from bridge inspection report provided by one Ministry of Transportation in Canada. Quantities inspected and reported in each of the four condition states are presented in Table 5.The bridge elements condition indices estimated using the proposed BECI are 66, 22.5, 55, 55 and 58 for Deck, Beams, Abutments, Piers and Barrier, respectively.

In order to evaluate the structural importance of the bridge elements, a bridge expert that is currently involved in major bridge evaluation and rehabilitation projects, was required to compare the different elements. The elements are compared in pairs with respect to the degree that these elements can affect the structural integrity and safety of the bridge. Table 5 presents bridge inspection results extracted from an inspection report. The different elements have different structural importance and the element's structural importance increases as the element condition index decreases. Table 6 presents the matrix of comparison of the different elements and the structural weight of each element developed using the eigenvector approach.

Table 5. Bridge inspection results.

Element	Total quantity m2	Excelle-nt m^2	Good m^2	Fair m^2	Poor m^2
Deck	1000	500	100	200	200
Beams	600			300	300
Abutments	100		50	50	
Piers	100		50	50	
Barrier	200		120	80	

Table 6: Pairwise comparison of the elements structural importance provided by an expert.

	Deck	Beams	Abut-ments	Piers	Barrier	Weight
Deck	1	1/7	1	3	2	0.127
Beams	7	1	7	9	7	0.630
Abutments	1	1/7	1	3	1	0.110
Piers	1/3	1/9	1/3	1	1	0.056
Barrier	1/2	1/7	1	1	1	0.076

From the table above λ_{max} = 5.22, CI = 0.06 and CR = 0.051. Since CR is less than 10%, the judgment made to develop the matrix of relative importance was consistent. It is clear that the deteriorated beams have the highest structural importance value and it can be a critical component for the structural integrity and safety of the bridge.

Finally the bridge overall condition index is calculated using Equation 2 as follows:

$$BCI = 66\times0.127 + 22.50\times0.630 + 55\times0.110 + 55\times0.056 + 58\times0.076$$
$$= 36.10$$

The proposed methodology in this research evaluates both the physical condition and the structural importance of the bridge elements using the inspection results and experts' knowledge and judgment. The developed BCI is proposed as a unified bridge condition indicator for the existing concrete bridges.

Conclusion

In this paper, bridge condition assessment practice adopted by certain ministries of transportation in Canada is reviewed and a methodology to perform bridge condition evaluation is developed. The methodology proposes a bridge element condition index which is based on remaining value of the deteriorating quantities of the element. The proposed element condition index benefits from bridge element inspection guidelines provided by the OSIM.

The developed methodology uses the AHP to evaluate the structural importance of the bridge elements and the MAUT to combine the elements condition rating and structural importance into an overall bridge condition rating.

The proposed methodology has a definite advantage over the weighted average approach since the weighted average does not reflect the exact condition of the bridge elements. Another significant advantage of the proposed methodology is that the structural importance values for the various elements are developed specifically for each bridge based on the experience and judgment of bridge expert. This approach is superior to using general structural importance values.

For these advantages, the developed BCI is proposed as a unified bridge condition evaluation technique for the existing concrete bridges.

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