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Defect-Based Urgency Index for Bridge Maintenance Ranking and Prioritization

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***Abstract*—**Bridge condition assessment and rating provide essential information needed for bridge management. This paper reviews bridge inspection and condition rating practices and introduces a defect-based urgency index. The index is estimated at the element-level based on the extent and severity of the different defects typical to the bridge element. The urgency index approach has the following advantages: (1) It facilitates judgment submission, i.e. instead of rating the bridge element with a specific linguistic overall expression (which can be subjective and used differently by different people), the approach is based on assessing the defects; (2) It captures multiple defects that can be present within a deteriorated element; and (3) It reflects how critical the element is through quantifying critical defects and their severity. The approach can be further developed and validated. It is expected to be useful for practical purposes as an early-warning system for critical bridge elements.

***Keywords*—**Condition rating, deterioration, inspection, maintenance.

I. Introduction

EXISTING bridge infrastructure has deteriorated rapidly in recent years due to increase traffic volume and other service requirements. For instance, the 2013 Report Card for America's Infrastructure estimated that more than two hundred million vehicles take daily trips across deficient bridges in the major metropolitan regions in the United States. The report also alarmed that one in nine of the country's bridges are rated as structurally deficient. The average age of the 607,380 bridges in the United States was 42 years in 2013 [1]. To manage existing bridge infrastructure, Bridge Management Systems (BMSs) have been developed and used to maintain bridges within acceptable limits of safety and serviceability.

The main functions of BMSs include administrative planning, programming, and implementation. BMS main modules are condition rating, deterioration modeling, and decision optimization. These functions are needed for each bridge (project level) and for the full network of bridges within a system (network level) [2]. Data and information including inspection reports, deterioration models, available budget, available Maintenance, Repair and Replacement (MR&R) strategies and their costs are all vital inputs to any BMS. Condition rating is one of the important steps in bridge management. Bridge condition rating is completed based on condition assessment information typically collected through bridge inspection [3].

The concept of Bridge Health Index (BHI) was developed for California Department of Transportation as a performance measure and it is used in California for allocation of resource [4]. The BHI introduced enhanced performance measure; however, the approach has some limitations. This paper reviews bridge inspection practices in North America and discusses the concept of bridge health index. Then, the paper introduces an alternative approach that focuses on the degree of defects and deterioration of bridge elements instead of health.

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II. Bridge Inspection and Rating Practices in North America

Among the commonly-used bridge condition assessment and rating systems in the United States are the National Bridge Inventory (NBI) and Pontis (currently known as BrM) [5]. In 1968, the Federal Highway Administration (FHWA) in the United States developed the National Bridge Inspection Standards. The standards require the inspection of all bridges on public roadways in the United States on a periodic basis. Also, the FHWA developed a program for translating bridge condition data of commonly recognized bridge elements into NBI condition ratings format for the purpose of data submittal to FHWA. The program enabled bridge inspectors to report condition information in a format that can be used for bridge management and satisfies the NBI data collection requirements. The FHWA has made the documentation of the National Bridge Inspection Standards available in the association website [6].

To facilitate the inspection process, the Bridge Inspector's Training Manual [7] divides the three major components of a bridge (Deck, Superstructure, and Substructure) into 13, 16, and 20 elements, respectively, as shown in Table I. In addition, this manual provides the basic guidelines for bridge inspection, the different types of bridge deterioration and their common causes, and procedures for rating the condition of the different bridge elements.

The other commonly used system for bridge rating is Pontis. It is a comprehensive BMS developed as a tool to assist in the challenge of managing bridge infrastructure [5]. Pontis uses element-level inspection approach described in the AASHTO Guide for Commonly Recognized (CoRe) Structural Elements [8]. In Pontis, bridge deck inspection results are obtained from assessing the percentage of spalling and delamination in the deck and measuring the width and spacing of cracks [9]. Colorado Department of Transportation [10] suggested condition rating according to the extent of these defects. These values are presented in Tables II and III.

TABLE I
BRIDGE ELEMENTS [7]

Deck	Superstructure	Substructure
1. Wearing surface	1. Bearing devices	1. Bridge seats
2. Deck condition	2. Stringers	2. Wings
3. Curbs	3. Girders	3. Back wall
4. Median	4. Floor beams	4. Footings
5. Sidewalks	5. Trusses	5. Piles
6. Parapets	6. Paint	6. Erosion
7. Railings	7. Machinery	7. Settlement
8. Paint	8. Rivets-Bolts	8. Pier-cap
9. Drains	9. Vibrations	9. Pier-column
10. Lighting	10. Welds	10. Pier-footing
11. Utilities	11. Rust	11. Pier-piles
12. Joint leakage	12. Timber decay	12. Pier-scour
13. Expansion joints	13. Concrete cracks	13. Pier-settlement
	14. Collision damage	14. Pier-bents
	15. Deflection	15. Concrete cracks
	16. Alignment of members	16. Steel corrosion
		17. Timber decay
		18. Debris seats
		19. Paint
		20. Collision damage

TABLE II
SUGGESTED CONDITION STATES FOR BARE CONCRETE DECK [10]

Condition State	Description
1	No repaired areas, no spall/delaminations exist
2	Repaired areas/spalling/delamination area is 2% or less of deck surface
3	Repaired areas/spalling/delamination area is 10% or less of deck surface
4	Repaired areas/spalling/delamination area is more than 10% but less than 25% of deck surface
5	Repaired areas/spalling/delamination area is more than 25% of deck surface

TABLE III
SUGGESTED CONDITION STATE RATINGS FOR DECK CRACKING [10]

Crack width (mm)	Condition states for cracks in concrete deck Spacing of cracks (m)			
	>3	2-3	1-2	<1
<1	1	1	2	3
1-2	1	2	3	4
2-3	2	3	4	4
>3	3	4	4	4

Ministries of Transportation of the different Canadian provinces have been actively working on bridge inspection programs. Ontario, Alberta and Quebec have developed and used BMSs and developed customized inspection standards. For instance, Ontario Structure Inspection Manual defines four condition states possible for bridge elements, namely: Excellent, Good, Fair, and Poor [11]. The manual provides guidelines and procedures to help bridge inspectors in identifying defects, assessing their conditions and assigning the appropriate condition state. Also, the manual provides a procedure to collect condition data of bridge elements and to complete the inspection form. The inspector assesses material conditions of each element and measures the quantity of the element in each condition states. The quantity of the element is measured using appropriate units based on the element geometry such as meter for length and square meter for areas.

Inspectors estimate quantities of the inspected element that are in Good, Fair and Poor. The Excellent quantity is the total quantity of the element minus quantities in Good, Fair and Poor. OSIM [11] provides different forms to collect data during bridge inspection. Fig. 1 shows customized inspection form prepared based on the OSIM [11] requirements. The inspector estimated that 300 m^2 of the total deck surface area (bottom and top) is in good condition state and 52 m^2 is in poor condition state.

Bridge Structure Inspection Report
Ministry of Transportation - Structure Section - Bridge Inspection and Management Unit

Inspection Report No.: 7	Location: WXI555	Province: XXX
Bridge No.: 007	Over: HW14	Ditrict: 100
Inspection Date: 30-March-2014	Temperature During Inspection: 6°C	Owner: Provience

Structure Type	**Deck Type and Material**
Superstructure Type: Prestressed Concrete Girders	Deck Type: CIP Concrete
Number of Main Spans: 2	Wearing Surface: Monolithic Concrete
Number of Approach Spans: 2	Deck Protection: None
Deck Type: CIP Concrete	
Age and Service	**Age and Service**
Year Built: 2000	Year Reconstructed: N/A
Service On: Roadway	Service Under: Highway
Lanes on the Structure: 2	Lanes Under the Structure: 4
ADT: 1200	% Trucks of ADT: 5
Year of ADT: 2005	Total Quantity
Inspection Condition and Results	**Deck Dimensions**
Accessibility: □ Limited Insp. x Full Access	Length: 22 m
Environment: □ Benign □ Moderate □ Severe	Width: 8 m
Unit of measurements: m^2	Vertical Clearance: 7.5 m
Quantity in Excellent: 0	Thickness: 0.22 m
Quantity in Good: 300 m^2	
Quantity in Fair: 0	
Quantity in Poor: 52 m^2	

Comments: Previously repaired delaminated area is delaminated again

Recommended Work: □ None □ 6-10 years x 1-5 years □ <1 year □ Urgent

Fig. 1 Customized Inspection Report Based on OSIM [11] Requirements

As mentioned earlier, [4] proposed a new performance measure for bridges. This measure is known as the health index (HI) and determines the remaining bridge asset value. The HI is proposed to measure structural condition of a single bridge or a network of bridges by using condition data extracted from bridge inspection reports. The concept is developed based on the element asset value. Bridge element has an initial asset value when the element is in new condition and this value decreases as the element deteriorates. The equations to compute the HI is as:

$$HI = (\Sigma CEV / \Sigma TEV) \times 100 \quad (1)$$

where CEV is current element value and TEV is total element value.

$$TEV = \text{total element quantity} \times \text{failure cost of element} \quad (2)$$

$$CEV = \Sigma(\text{quantity condition state} \times \text{weighing factor}) \times \text{failure cost of element} \quad (3)$$

Reference [12] criticized the HI for being an overall representation of a bridge or a network condition which does not accurately reflect the conditions of specific bridge elements since the HI is an average of the conditions of the bridge elements. This paper introduces an element level urgency index estimated based on quantity and severity of elements defects.

III. Defect-Based Bridge Element Urgency Index

Available health indexes focus on reflecting the positive aspect of the bridge condition which is the health of the bridge. This is might be related to the need that reporting to managers and ministries of transportation officials is required to convey the positive aspect. However, in this research, it is suggested that the degree of defects and deterioration to be the deriving factor for condition indicators. As a result, the proposed urgency index in this research focuses on the degree of defect and deterioration and uses them to specify urgency for intervention. The higher the urgency factor, the more urgent the bridge element is for intervention. The concept of this urgency factor is based on quantifying the defects and the degree of severity. Initially, when an element is in an Excellent condition state, it has 0% of its quantity defected and as a result is assessed at the lowest urgency of 0. When the element deteriorates to a Good condition state, the percentage of defects has increased and its urgency for intervention has increased as well so the index will increase reflect the situation.

If different areas of the bridge element have different defects, then the element's urgency index is estimated based on the area quantity of each condition state and its corresponding weight. Bridges are typically made of three main components: 1) deck, 2) Substructure, and 3) Superstructure. Each of these components can be divided into elements and condition rating of the main components can be performed by assessing the conditions of the main elements of the component under consideration. For the scope of current paper, the focus is on the bridge deck. The bridge deck is divided into four main elements: Wearing Surface, Deck Top, Deck Bottom and Drainage System. Bridge deck defects and their weights are identified based on reviewing bridge inspection manuals and using the authors' judgments. The breakdown and the weights are provided in Table IV.

Using weights in Table IV, each deck element can be rated as:

$$EI = (\sum Qi \times ESi \times SWi) \times 100 \quad (4)$$

where EI is the element index, Qi is the percentage of deck area affected by defect i and SWi is the sub weight of defect i. The ESi is the element severity index obtained as A, B, C or D based on the inspector assessment for the defect severity and percentage area affected by the defect. This severity index is obtained from Fig. 2 extracted from [13]. The values for A, B, C and D ratings are assigned to be 10, 50, 75 and 100, respectively.

TABLE IV
RELATIVE WEIGHTS OF BRIDGE DECK ELEMENTS AND DEFECTS

Deck Element	(Weight)	Defect	(Sub weight)
Wearing Surface	0.20	-Potholes	0.30
		-Cracking	0.30
		-Rutting	0.10
		-Rippling	0.10
		-Loss of Bond	0.20
Deck Top	0.40	-Delamination/Spalling	0.30
		-Cracking	0.20
		-Corrosion of R/C	0.30
		-Pop-outs	0.10
		-Scaling	0.10
Deck Bottom	0.30	-Delamination/Spalling	0.40
		-Cracking	0.20
		-Corrosion of R/C	0.30
		-Scaling	0.10
Drainage System	0.10	-Pipe Breakage	0.75
		-Deterioration of Components or connections or fasteners	0.25

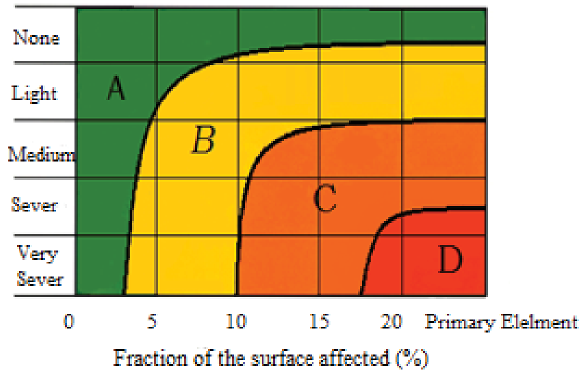

Fig. 2 Grade mapping over defect severity and extent [13]

The urgency index can be estimated by aggregating all elements indexes as:

$$UI = \sum \text{Element Index } j \times Wj \quad (5)$$

where UI is the urgency index, j represents the Wearing Surface, the Deck Top, the Deck Bottom and Drainage System, and Wj values for these elements are 0.2, 0.4, 0.3 and 0.1, respectively.

IV. Case Example

Data provided in Table V depict the measurements of defects that were detected on various elements of a bridge deck. Defects were detected by means of visual inspection or non-destructive evaluation.

The condition index of each of the four deck elements can be estimated using (1). For example, the wearing surface element is evaluated by aggregating the assessments of potholes, cracking, rutting, rippling, and loss of bond. Only potholes and cracking are present in the above case. The inspector assessed that total of 20% of the wearing surface is severely deteriorated while in 15% of the area has light deterioration. Based on 20% of the sever defects, the rating is C and based on 15% light defects, the rating is B. The values for B and C are 50 and 75, respectively. The element index of the wearing surface is: (20% × 75 × 0.3 + 15% × 50 × 0.3) × 100 = 67.5

TABLE V
DEFECTS COLLECTED FROM DETAILED INSPECTION REPORT OF THE BRIDGE DECK

Elements	Defect	Observation (Severity & Extent)
Wearing Surface	Potholes	Severe (10%)
	Cracking	Light (15%), Severe (10%)
	Rutting	None
	Rippling	None
	Loss of Bond	None
Deck Top	Delamination/Spallig	V.severe (7%)
	Cracking	Medium (8%), Light (32%)
	Corrosion of R/C	V.severe (12%)
	Pop-outs	None
	Scaling	None
Deck bottom	Delamination/Spallig	V.severe (2%)
	Cracking	Medium (20%)
	Corrosion of R/C	Medium (18%)
	Pop-outs	None
	Scaling	None
Drainage System	Pipe Breakage Loosening/ Deterioration of Components or connections or fasteners	None

The same procedure is applied to assess the index for the remaining elements.

- Deck top: (7% × 50 × 0.3 + ((8% × 50 + 32% × 50) × 0.2) + 12% × 75 × 0.3) × 100 = 77.5
- Deck bottom: (2% × 10 × 0.4 + 20% × 50 × 0.2 + 18% × 75 × 0.3) × 100 = 61.3
- Drainage System: 0 (No deterioration so no urgency)

The overall urgency index can be estimated based on the index value and weight of each element. The final aggregated assessment output for the bridge deck can be estimated using (2): 0.2×67.5 + 0.4×77.5 + 0.3×61.3 + 0.1×0 = 62.9

The urgency indexes for bridge deck of all bridges in the network are estimated. Bridges with the higher urgency indexes are prioritized for intervention by applying appropriate rehabilitation intervention to remedy defects affecting bridge conditions.

V. CONCLUSION

This paper introduced an urgency index to assist bridge managers in identifying deteriorated bridge elements and to prioritize them for intervention. The urgency index focuses on the defects observed during bridge inspection which can be more significant indication for maintenance decisions than assessing the degree of bridge health. The urgency index facilitates the assessment task. Instead of submitting judgments regarding the rating of the bridge element such as Excellent and Fair, bridge inspectors are required to quantify extent of defects and their severity. The extent and severity are quantified and input into the urgency index equations proposed in this research. The output is the urgency index of the element. This is particularly important to reduce the impact of uncertainty and subjectivity inherent in bridge inspector judgments. The urgency index is demonstrated with a case example and is proposed to be evaluated further for potential use in practice. The authors recommend that a similar approach could be implemented for the visual inspection of roadway pavement surface. For a future research, the authors recommend to utilize artificial intelligence techniques, such as fuzzy logic, to deal with the uncertainty and subjectivity that could be associated with the proposed approach.

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