A NOVEL COST AND CONDITION BASED INDEX FOR ASSESSMENT OF BRIDGES

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ABSTRACT
Bridges are key components in transportation systems in Ohio, and are essential in supporting various economic activities at local and state levels. These structures deteriorate differently due to differences in exposure to various environmental stressors and service loads, and having diverse ages, configurations, and structural features. Moreover, the amount of budget to maintain, repair and replace bridges in Ohio which has the second largest number of bridges in the U.S. is limited. These factors, among others, pose a challenge for evaluating the performance of these structures and managing their safety and serviceability. This study presents a practical and efficient measure called bridge condition index (BCI) for reliable condition assessment of Ohio bridges through effective utilization of ODOT's bridge databases. Ohio BCI (OBCI) is intended to evaluate bridges at element-, component-, bridge-, and network-levels and to reflect the impact of defects as well as condition enhancement of individual elements on the condition-state of the system. In order to compare direct and indirect consequences of various conditions of bridges on users and agencies, a unified metric based on cost is proposed for the OBCI formulation. This index is demonstrated for a real bridge in Ohio. To examine the efficiency of the OBCI, the results are compared to Bridge Health Index which is a common bridge performance metric. Furthermore, the ability of OBCI to account for effects of bridge serviceability features such as average daily traffic is shown. The proposed metric can assist in proper maintenance of transportation systems and enhancement of their serviceability and safety.

INTRODUCTION

Ohio has the second largest inventory of bridges in the United States. These bridges are comprised of various ages, configurations, and structural features, and are exposed to various environmental conditions and service loads. These factors, among others, pose a tremendous challenge for evaluating the performance of these assets and managing their safety and serviceability. A reliable and objective index is needed to effectively utilize available data to evaluate the health conditions of Ohio bridges. The new metric should consider multiple attributes of bridge performance with respect to bridge preservation and vulnerability using a single number. In addition, this measure must be reliable to allow objective assessment of the long-term performance of bridge programs at multiple levels of stakeholders such as county, district, and state levels. It also needs to enable highway agencies to compare and prioritize bridges in a network, identify effective MR&R actions, and properly allocate budget over time for a single bridge or a network of bridges. Such a metric should help effective communications about bridge conditions, required budget, and performance of bridge programs with various stakeholders such as the public, legislature, and bridge program directors.

Bridge performance measures are used as a critical tool to manage and operate a large number of bridges in transportation systems. The choice of an appropriate performance measure strongly depends on agency policies, level of decision-making, and bridge type, among other factors (*1*). Consequently, various types of metrics have been developed over the years for different purposes. These metrics are being used to support goals such as preservation maintenance (also sometimes referred to as preventive maintenance) and allocation of funds for rehabilitation/replacement and improvement of bridges. These metrics include, among others, national bridge inventory rating (NBI), Deficiency Rating (DR), Sufficiency Rating (SR), Load Rating (LR), Bridge Health Index (BHI), Denver BHI, Geometric Rating (GR), and Vulnerability Rating (VR). These performance measures were proposed/implemented by state DOTs, FHWA, NCHRP, and other researchers. In many indices such as SR (*2*) and DR (*3*), subjective weight factors are considered to account for structural and serviceability failure modes, whereas in reality, the likelihood of these failure modes, as well as their corresponding consequences, depend on the severity of the problems and the environment where bridges are located. In BHI and Denver BHI, first, health indices of elements of similar type (e.g. columns, girders, etc.) are determined based on the percentage of elements in each of the condition-states. Using the derived health indices and a set of weighting functions, the health index of the entire bridge is evaluated (*4-6*). The weighting functions are subjectively defined for each element to represent the importance and criticality of that element for the safety and serviceability of the entire bridge. However, the criticality of an element should be objectively quantified based on consequences on users and agencies. A solution to improve the objectivity of bridge performance metrics is to account for impacts of various potential consequences of condition-states of bridges in terms of expected costs that are expressed in a monetary unit.

In order to address limitations of existing indices and provide a metric with the desired features explained at the beginning of this section, this paper presents a novel cost-based performance metric called Ohio Bridge Condition Index (OBCI). The considered cost categories include: (1) implementation costs referring to costs of applying upgrades or repair actions. An important feature of the proposed framework is the incorporation of a comprehensive list of incurred costs to reliably determine consequences of such repair/upgrade actions. (2) structural/serviceability failure costs referring to costs of consequences for the existing condition of bridges. In the rest of the paper, the scope of the OBCI is presented, the involved cost terms are explained, minimum allowable thresholds for the condition-state of bridge elements are introduced, formulations of two versions of OBCI are developed, the proposed OBCI formulations are applied to a case study bridge from ODOT`s bridge inventory, and conclusion remarks are presented.

OHIO BRIDGE CONDITION INDEX (OBCI)

In the proposed OBCI, direct and indirect consequences of various conditions of bridges for users and agencies, are incorporated through a unified metric based on cost. In bridge management, there are two types of events that have consequences for users and agencies: potential structural/operational failures of bridges and Maintenance, Repair and Replacement (MR&R) actions performed on bridge elements; both of these are functions of the condition-states of bridge elements, among other factors. Thus, cost terms in OBCI can be classified into two groups:

- Implementation Cost: This cost is estimated when MR&R actions are planned to be applied to bridge elements according to the results of routine inspections. It includes element-level costs of implementing MR&R actions. The implementation cost contains user and agency costs. Agency costs are the direct money that is paid by the responsible agency for executing MR&R actions on bridge elements. This cost includes the costs of administration, engineering, crew and equipment mobilization, maintenance of traffic, and costs of executing MR&R actions on bridge elements. User costs are the costs incurred on users, i.e. drivers and passengers, due to the implementation of MR&R actions. This cost may include incurred costs of posting load and clearance restrictions, extra vehicle operation, delay time on users, and excess emission. Implementation costs are elaborated in the next sections.
- Structural/Operational Failure Cost: The sum of all user and agency costs in the foregoing implementation cost is needed to maintain, repair or replace elements of a bridge. On the other hand, if required MR&R actions are not performed on the bridge, structural or operational failures may occur. Thus, the quantification of consequent failure modes in terms of monetary units helps responsible agencies with the decision-making process through cost-benefit analyses. In addition, each failure mode has a likelihood of occurrence. Thus, for the purpose of quantifying the consequences of failure modes, the concept of risk, i.e. the product of the likelihood and the cost of structural/functional failure modes, can be applied in OBCI. These costs of consequences are expected costs due to structural/operational failures of bridges that can potentially occur as a result of deterioration, fatigue, flooding and scour, among other factors. When a failure mode occurs, both users and agencies are affected. The responsible agency repairs the damaged elements. Thus, all of the cost terms of the agency costs that were mentioned for the implementation costs, should be considered as the agency costs for the "structural/operational failure costs".

Scope of the OBCI Model

OBCI is intended to evaluate bridges at element-, component-, bridge-, and network-levels. Each level is defined as follows:

- Element: OBCI evaluates all elements of the same type in a bridge. For instance, OBCI presents a single condition-index for all of the pier columns existing in a bridge. Following the new AASHTO recommended condition-rating system (*7*), ODOT provides an overall condition-state rating for elements in a scale from 1 to 4 (*8*). These elements can be any of the 68 element types that are categorized into four groups of: National Bridge Elements (NBE), Bridge Management Elements (BME), Agency Developed Elements (ADE), and defects.

- Component: OBCI evaluates the overall condition of a group of different elements that together serve a role in structural integrity and/or serviceability of bridges. Following AASHTO (*7*) and ODOT (*8*), the subsequent components are available in the new inspection reports: Approach, Deck, Superstructure, Substructure, Culvert, Channel, and Sign/utility.
- Bridge: OBCI evaluates the condition index at the bridge-level considering the condition-state of the entire constituent elements of that bridge.
- Network: OBCI evaluates the overall condition of a portfolio of bridges in a region, district, county, and the State of Ohio.

This performance measure reflects the impact of defects as well as condition enhancement of individual elements on the condition-state of the system in each of the foregoing levels. In the rest, two versions of the OBCI are presented and the application of these indices are demonstrated for one of the ODOT`s bridges.

OBCI Models with Minimum Thresholds

Generally, there is a trade-off between implementation and structural/operational failure costs in the OBCI; the more costly the MR&R action, often the better the long-term performance of benefitted elements. Evaluation of these costs requires failure mode identification and likelihood estimation, which can be very time consuming considering that each bridge type and configuration may have very different modes of failure. Instead, as a practical alternative for the incorporation of structural/operational failure risk costs in the OBCI, minimum thresholds are established to define unacceptable condition-states for bridge elements. This provides an incentive to perform MR&R actions before the state of bridges becomes critical. In addition, these minimum acceptable condition-states assure an acceptable level of safety and serviceability of bridges for the public, and reduce the likelihood of failure modes to the extent that the risk costs become fairly negligible compared to implementation costs. Therefore, only implementation costs are incorporated in the OBCI framework. A general flowchart of the proposed framework is shown in Figure 1.

Minimum required OBCI

On a rational basis, minimum thresholds should be set based on the importance of elements for the safety and functionality of the bridge system. At component-, and/or bridge-levels, 21 state DOTs have set up target values for the condition of their bridge assets (*9*). For instance, state of Ohio defines 15% as the maximum allowable percentage for the area of its bridge decks with NBI general appraisal ratings less than 5. In line with the most recent AASHTO recommended condition-state rating system, at element-level, authors have defined the following minimum thresholds:

- The percentage of NBE, defects and primary elements of ADE in condition-states 3 should be less than 2%, while no quantities of these elements should be in condition-state 4.
- The percentage of BME and non-primary ADE elements in condition-state 3 and 4 should be less than 10%.

In the future, effects of other factors will be explored to develop more representative minimum thresholds. For bridges where the above criteria are not satisfied, MR&R actions should be taken so that the condition-state of all elements is at or above the corresponding minimum threshold. On this basis, minimum OBCI can be expressed as:

$$OBCI_{min} = 1 - \frac{\sum cost\ of\ meeting\ minimum\ thresholds(\$)}{replacement\ cost(\$)} \quad (1)$$

where *replacement cost* is the total cost of replacing the system including the associated implementation costs. In fact, $OBCI_{min}$ represents the proximity of the system to meet all the minimum thresholds. Decomposing the costs into agency and user costs for all the elements, $OBCI_{min}$ can be written as:

$$OBCI_{min} = 1 - \frac{AC^{min} + UC^{min}}{RC} \quad (2)$$

where RC is the replacement cost of the system, and AC^{min} and UC^{min} are the incurred agency and user costs (implementation costs) as a result of performing MR&R actions on bridge elements in order to meet the minimum condition-state thresholds. Detailed formulations of $OBCI_{min}$ for evaluation at element-, component-, bridge-, and network-levels are provided in Table 1.

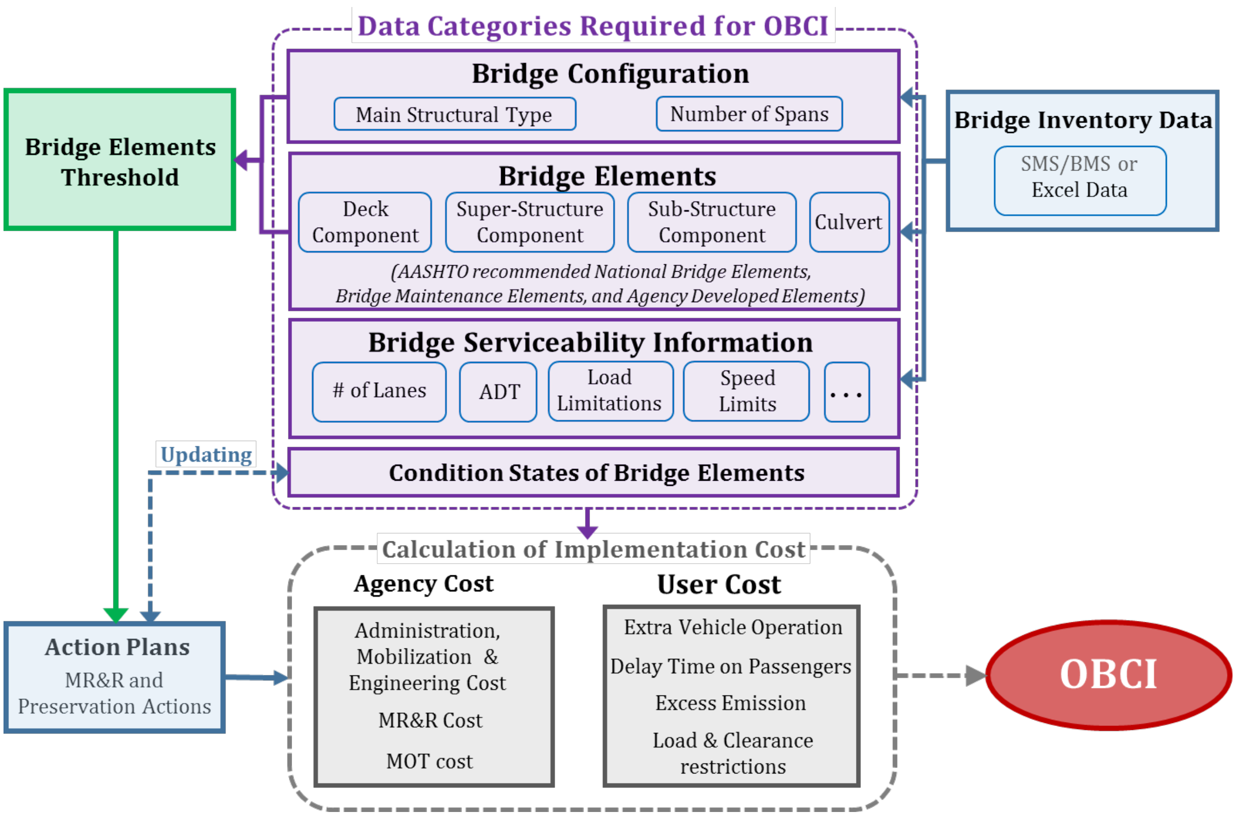

FIGURE 1 General flowchart of the proposed OBCI with minimum condition-state thresholds

TABLE 1 Formulation of $OBCI_{min}$ for element- component-, bridge- and network-levels

Scope	$OBCI_{min}$	
Element	$OBCI_{min} = 1 - \frac{(AC_E^{min} + UC_E^{min})}{(AC_E^{rep} + UC_E^{rep})}$ $AC_E^{min} = MOT_E^{min} + AEM_E^{min} + MR\&R_E^{min}$ $UC_E^{min} = LCR_E^{min} + DVE_E^{min}$ $AC_E^{rep} = MOT_E^{rep} + AEM_E^{rep} + MR\&R_E^{rep}$ $UC_E^{rep} = LCR_E^{rep} + DVE_E^{rep}$	(3)
Component	$OBCI_{min} = 1 - \frac{(AC_C^{min} + UC_C^{min})}{(AC_C^{rep} + UC_C^{rep})}$ $AC_C^{min} = MOT_C^{min} + AEM_C^{min} + \alpha_C^{min} \times \sum_{k=1}^{M_c} MR\&R_k^{min}$ $UC_C^{min} = LCR_C^{min} + DVE_C^{min}$ $AC_C^{rep} = MOT_C^{rep} + AEM_C^{rep} + \alpha_C^{rep} \times \sum_{k=1}^{M_C} MR\&R_k^{rep}$ $UC_C^{rep} = LCR_C^{rep} + DVE_C^{rep}$	(4)
Bridge	$OBCI_{min} = 1 - \frac{(AC_B^{min} + UC_B^{min})}{(\gamma \times A + UC_B^{rep})}$ $AC_B^{min} = MOT_B^{min} + AEM_B^{min} + \alpha_B^{min} \times \sum_{c=1}^{M_b} \sum_{k=1}^{M_c} MR\&R_{k,c}^{min}$ $UC_B^{min} = LCR_B^{min} + DVE_B^{min}$ $UC_B^{rep} = LCR_B^{rep} + DVE_B^{rep}$	(5)
Network	$OBCI_{min} = 1 - \frac{(AC_N^{min} + UC_N^{min})}{(\sum_{b=1}^{M_n} \gamma_b \times A_b + UC_N^{rep})}$ $AC_N^{min} = MOT_N^{min} + AEM_N^{min} + \alpha_N^{min} \times \sum_{b=1}^{M_n} \sum_{c=1}^{M_b} \sum_{k=1}^{M_c} MR\&R_{k,c,b}^{min}$ $UC_N^{min} = LCR_N^{min} + DVE_N^{min}$ $UC_N^{rep} = LCR_N^{rep} + DVE_N^{rep}$	(6)

In this table, AC_E^{min} and UC_E^{min}, AC_C^{min} and UC_C^{min}, AC_B^{min} and UC_B^{min}, and AC_N^{min} and UC_N^{min} are the costs incurred on agency and users for reaching the minimum condition-states of the constituent elements of the element set *E*, component *C*, bridge *B*, and network *N*, respectively. The element-, component-, bridge-, and network-level agency costs of Administration, Engineering and Mobilization (AEM), and Maintenance of Traffic (MOT) are denoted by AEM_E, AEM_C , AEM_B , AEM_N , MOT_E , MOT_C , MOT_B , respectively. Furthermore, the element-, component-, bridge-, and network-level user costs of Load and Clearance Restriction (LCR), and Delay time, Vehicle operation, and Excess emission (DVE) are denoted by LCR_E, LCR_C, LCR_B, LCR_N, DVE_E, DVE_C, DVE_B, DVE_N, respectively. Where these costs correspond to the cost of reaching the minimum required condition-state, they are specified with a superscript *min*, and where these cost represent the associate cost of replacement, superscript *rep* is used. The MR&R cost of bringing the condition-state of element k of component c of bridge b to its minimum threshold is denoted by $MR\&R_{k,c,b}^{min}$. In order to account for reductions in the MR&R costs as the scale of the project increases, a reduction coefficient, α, is considered for the total MR&R costs for component-, bridge-, and network-level OBCI. These factors range from 0 to 1. The subscript for this factor represent the scope of the project, and the superscript indicates the amount of improvement achieved by the MR&R actions. For example, α_B^{min} is the reduction coefficient applied for the MR&R cost when all elements of the bridge are improved together to meet their minimum acceptable condition-state. Unlike elements and components, the replacement cost of a bridge is usually expressed in terms of bridge type and deck area. Therefore, in Equation (*5*) and Equation (*6*), γ_b is the unit replacement cost per deck area of bridge b, and A_b is the deck area of the bridge. Finally, M_c, M_b, and M_n are the number of existing elements, components, and bridges, respectively. Following Equations (*3*)-(*6*), if the sum of required costs to improve the condition-state of elements, components, or bridges in the system exceeds the replacement cost of the system, it will be replaced with the replacement cost of the system.
The proposed $OBCI_{min}$ has the following features:

- $OBCI_{min}$ evaluates the proximity of the system to meet corresponding minimum thresholds for acceptable condition-states considering user and agency costs of implementing MR&R actions.
- $OBCI_{min}$ provides decision-makers with a set of MR&R actions that incur minimum user and agency costs to reach minimum thresholds. This feature is useful for emergency decision-making, and when the available budget is limited (i.e. taking the least costly decision, while providing the minimum required level of safety and operability).

OBCI indicating the Current Condition
A true index for the performance of a system needs to compare the state of the system with its like-new condition. On this basis, other than $OBCI_{min}$that is intended to reflect the minimum necessary amount of work, $OBCI_{current}$ is expressed as:

$$OBCI_{current} = 1 - \frac{\sum cost\ of\ going\ back\ to\ the\ like\ new\ condition(\$)}{replacement\ cost(\$)} \tag{7}$$

According to Equation (*7*), $OBCI_{current}$ ranges from 0 to 1; the more healthy the condition-state of the bridge, the closer $OBCI_{current}$ to 1. The structure of the formulation of $OBCI_{current}$ at element-, component-, bridge-, and network-levels is identical to corresponding formulations of

$OBCI_{min}$ presented in Equations (*3*)-(*6*). However, the superscript of the cost terms in the numerators should be changed to 1, indicating the cost to improve to the like-new condition-state. Therefore, $OBCI_{current}$ compares the current condition of the system with the like-new condition to indicate how close the system is to its desirable condition.

Cost Terms in OBCI

As previously mentioned, cost terms in OBCI are the costs imposed on users and the responsible agency due to performing MR&R actions following routine inspections on bridge elements. These costs include: agency costs of MR&R, MOT, and AEM, and user costs of DVE, and LCR. The agency and user costs can be estimated based on available information about bridge configurations and inspection data. This information can be categorized into three groups: bridge configuration features, bridge serviceability features, and the types of bridge elements (See Figure 1). These three categories of information are mostly available in inspection reports. In the rest of this section, the derivation process of each of the agency and user cost terms using the aforementioned bridge information categories are explained.

Agency Cost

Maintenance, Repair, and Replacement Cost (MR&R) The type and extent of MR&R actions in the OBCI framework depend on the following factors:

- Material and type of elements
- The current condition-state of the elements
- The target condition-state of the elements: Often more costly corrective actions result in more improvement in the condition-state of an element. Thus, decision-makers may decide to evaluate the performance of bridges under several improving actions, each of which incurs certain cost and imposes certain improvement in the condition-state of elements.

Using the above procedure and ODOT costs for MR&R actions, the unit costs of performing MR&R actions are identified. Then, for calculating the total cost of performing MR&R actions on bridge elements, these unit cost values are multiplied by the amount of elements that are identified to require corresponding actions.

Maintenance of Traffic Cost (MOT) According to ODOT Office of Estimation, as of January 2016, maintaining traffic using "three laborers, one arrow board, one truck with attenuator, and one truck/flatbed for barrel replacement and removal" costs approximately $260/hour. If any police enforcement should be used for the maintenance of the traffic, an additional cost of $65/hour for each police car will be added to the MOT cost. Police enforcement is assumed to be present at the location of the project, if more than 40% of the bridge lanes is closed for repair actions. Since on weekends no worker is present, the cost of MOT is reduced to the equipment that direct the traffic; for those periods, the $260/hour unit cost is reduced by 60%. In other words, the cost of equipment and labors are considered to be 40% and 60% of the total cost, respectively. In addition, the $65/hour cost of police enforcement is not considered for these days. If $T_l^{t'}$ is the number of working days required for performing l-level project type *t*, with l and t varying among element-, component-, bridge-, or network-levels, and project types of 1, *min*, or *rep* (explained before), the minimum number of weekends that the project faces is $\left\lfloor \frac{T_l^{t'}}{7} \right\rfloor$, where $\lfloor\ \ \rfloor$ is the floor of the ratio $\frac{T_l^{t'}}{7}$. On the other hand, based on information provided by ODOT, the average number of hours that bridge laborers work is 8 hours/day. Therefore, MOT cost of an MR&R project of type *t* at l-level, i.e. MOT_l^t, can be calculated as follows:

$$MOT_l^t = \left(8 \times T_l^{t'} \times \$260 + 8 \times T_l^{t'} \times F^{N_{Cl}} \times \$65 + 16 \times T_l^{t'} \times 40\% \times \$260\right) + \left(2 \times \left\lfloor \frac{T_l^{t'}}{7} \right\rfloor \times 24 \times 40\% \times \$260\right) \quad (8)$$

In this equation, $F^{N_{Cl}}$ is a factor taking a value of 1 or 0, indicating the presence/non-presence of police officers, as a function of the number of closed lanes, N_{Cl}.

Administration, Engineering, and Mobilization Costs (AEM) The cost of administration, engineering, and mobilization for a project of type *t*, at l -level, i.e. AEM_l^t, can be estimated by:

$$AEM_l^t = \beta \times (MOT_l^t + MR\&R_l^t) \quad (9)$$

where β is an overhead factor, and is considered to be 0.25.

User Cost

User Delay, Vehicle Operation, and Excess Emission Costs (DVE) When MR&R actions are performed on bridge elements, the traffic on/under the bridge may be affected by the assignment of lower speed limits, and/or partial/complete closure of the bridge. Consequently, user costs due to delay, extra operation of vehicles, and excess emission from vehicles are incurred. The unit cost for such consequences for car and truck users, i.e. ρ_C and ρ_T, in year 2008, were reported as \$19.22/hour and \$51.88/hour, respectively (*10*). Using the average annual Consumer Price Index values reported in (*11*), the unit user costs for cars and trucks for year 2015 are derived as \$21.13/hour and \$57.04/hour, respectively. Then, considering an interest rate of 3%, these unit costs are calculated as \$21.76/hour and \$58.75/hour, for the year 2016.

It should be noted that user cost of DVE is incurred on average uniformly during the entire project time, T_l^t. Considering weekends and weekdays, T_l^t is equal to $T_l^{t'} + 2 \times \left\lfloor \frac{T_l^{t'}}{7} \right\rfloor$. Thus, the DVE user cost due to performing project type *t*, at l -level, i.e. DVE_l^t, can be computed as follows:

$$DVE_l^t = T_l^t \times (t_{ij}^{D/R} - t_{ij}^{O}) \times [(ADT - ADTT) \times \rho_C + ADTT \times \rho_T] \quad (10)$$

where $t_{ij}^{D/R}$ and t_{ij}^{O} are the required time to travel from the start point *i* of the bridge to its end point *j* by taking the detour/bridge with reduced speed limit, and taking the bridge at original posted speed, respectively. These parameters are derived using procedures developed by Bocchini and Frangopol (*12*).

User Costs of Load and Clearance Restriction (LCR) Load restriction postage to limit heavy vehicles due to poor conditions of bridge elements (mostly structural elements), and restrictions on the allowable horizontal clearance and vertical under-clearance of bridges due to performing some MR&R actions are other user cost terms that affect a certain group of users. Generally in these scenarios, the passage of certain types of trucks is restricted. Thus, similar to the process for computing DVE_l^t, the user cost for load and clearance restrictions when performing project type t, at l -level, i.e. LR_l^t, can be calculated as follows:

$$LCR_l^t = T_l^t \times (t_{ij}^{D/R} - t_{ij}^{O}) \times \left[ADTT^R \times \rho_T\right] \tag{11}$$

where $ADTT^R$ is the percentage of restricted trucks that should take the available detour.

CASE STUDY

General Information of the Case Study Bridge

For the demonstration of OBCI, a case study is conducted for a real bridge in Ohio. It is a two way, two lane bridge with nine continuous prestressed box beams, passing over a river. The length and width of the deck are 110 ft, and 34.5 ft, respectively. The bridge has a low ADT and ADTT of 50 and 5, respectively, and is on a path with no detour. Therefore, in order to perform any MR&R actions, the bridge should have at least one open lane. Moreover, the bridge is not posted for load and clearance restrictions. Table 2 presents the inspection data for this bridge including the quantity of elements in the four available condition-states.

Calculation of OBCI for the Case Study Bridge

As previously explained, element-, component-, bridge-, and network-level information is required for the calculation of the cost terms in both versions of the OBCI, i.e. $OBCI_{min}$ and $OBCI_{current}$. Some required information is collected from resources provided by ODOT, such as:

- Bridge configuration data: e.g. width and length, and the type of structural system.
- Type and material of bridge elements and the percentage of those element in each of the condition-states.
- Cost of several MR&R actions together with the condition-states before and after performing such actions. For example, as of 2016, patching the defected area of the concrete deck with condition-state 3 costs \$125/ft^2 and improves these areas to condition-state 2. On the other hand, if the entire deck should be replaced, the cost of \$100/ft^2 is incurred and the entire deck surface will be improved to condition-state 1.
- Bridge serviceability data: e.g. ADT, ADTT, number of lanes under and on the bridge.

For other required information, logical assumptions are made when necessary based on engineering judgment and consultation with ODOT. Some of such assumptions are:

- Given individual element-level information on the required time for performing MR&R actions, component- and bridge- level duration of work plans are estimated through a reduction factor, which is applied to the sum of individual element-level duration of MR&R actions in the work plan. These factors are considered to be 0.75, and 0.90, for component-, and bridge-levels, respectively.

- As presented in Equations (*4*)-(*5*), reduction factors are incorporated to account for the effect of scale in the computation of MR&R costs in component- and bridge- level OBCI, using element-level cost information (i.e. α factors in Table 1). These factors are considered to be 0.80, and 0.90, for component-, and bridge-levels, respectively.
- The replacement cost of the bridge (i.e. factor of γ in Table 1) is extracted from Caltrans (*13*); for the case study bridge, this value is \$315/ft^2. In order to update this cost for the State of Ohio, State (adjustment) factors given by US Army Corps of Engineers (*14*) are used.

Based on the aforementioned information, all the user and agency cost terms are estimated for element-, component-, and bridge-levels of the case study bridge. Then, $OBCI_{min}$ and $OBCI_{current}$ for these levels are computed following Equations (*3*)-(*6*), and the results are provided in Table 3. As seen, OBCI is not provided for the "alignment" of superstructure component. According to ODOT inspection manual (*8*) and AASHTO manual for bridge inspection (*15*), this item is a type of general deficiency for prestressed elements, which is among factors that determine the condition-state of concrete elements. The cost of repairing such a defect is considered within MR&R costs of concrete elements of the bridge. However, this does not apply to the scour item in the substructure component. Thus, OBCI is not assessed individually for the "alignment" of superstructure. It should be also noted that the variability of the cost values and other assumptions made in the framework may have non-negligible impacts on the results of the calculated OBCI values. Effect of these variations will be studied in the future.

As previously expressed, $OBCI_{min}$ compares the condition-state of the elements with the minimum allowable thresholds. Based on this index, approach slab and embankment, deck wearing surface, railing, drainage, and expansion joints require immediate repair; among these, approach embankment, which has the lowest index, is the most critical one. In bridge-level decision-making, $OBCI_{min}$ of 0.95 indicates that a repair work plan needs to be scheduled for this bridge so that this index becomes 1.0. Based on Equation (*5*), the minimum agency cost of improving the condition-state of the elements of this bridge to exceed the minimum acceptable thresholds, i.e. AC_B^{min}, is estimated to be \$130,810.

In addition, Table 3 indicates that the approach component with $OBCI_{current}$ of 0.57 has the lowest condition index among others, whereas $OBCI_{min}$ for this item is 0.78. This implies that, reaching the minimum acceptable condition-state for the approach component would cost 0.22 times the replacement cost incurred if a repair work plan is chosen for this component. However, the user and agency costs of improving this component to the like-new condition-state is 0.43 times the replacement cost which is half of the user and agency costs of replacing the component. Thus, replacing the approach component may be a reasonable plan.

TABLE 2 Quantity of the case study bridge elements in different condition-states

Element	Category of Element	Unit	QTY	Condition-State			
				CS1	CS2	CS3	CS4
Approach Items							
Approach Wearing Surface	ADE	Each	2	0	2	0	0
Approach Slab	BME	SF	810	146.5	405	202.5	56
Embankment	ADE	Each	4	0	0	0	4
Guardrail	ADE	Each	4	4	0	0	0
Deck Items							
Floor/Slab	NBE	SF	3795	3783	4	8	0
Wearing Surface	BME	SF	2970	1140	1140	540	150
Curb/Sidewalk/Walkway	ADE	LF	110	105	5	0	0
Railing	NBE	LF	220	180	30	10	0
Drainage	ADE	Each	2	0	0	2	0
Expansion Joint	BME	LF	69	14	15	40	0
Superstructure Items							
Alignment	Defect	Each	3	3	0	0	0
Beams/Girders	NBE	LF	990	987	1	2	0
Bearing Device	NBE	Each	72	72	0	0	0
Substructure Items							
Abutment Walls	NBE	LF	70.06	61.1	9	0	0
Pier Caps	NBE	LF	70.1	69.1	0	1	0
Pier Columns/Bents	NBE	Each	4	4	0	0	0
Wingwalls	ADE	Each	4	4	0	0	0
Scour	Defect	Each	4	4	0	0	0
Slope Protection	ADE	Each	2	2	0	0	0
Channel Items							
Alignment	ADE	LF	200	200	0	0	0
Protection	ADE	LF	200	200	0	0	0
Hydraulic Opening	ADE	EA	4	4	0	0	0
Sign Items							
Utilities	ADE	LF	220	220	0	0	0

Note: QTY=Quantity, CS1=Condition-state 1, CS2=Condition-State 2, CS3=Condition-state 3, CS4=Condition-state 4

Comparisons of OBCI with BHI for the Case Study Bridge

OBCI can help with decision-making in the presence of budget constraints. An example is provided to support this claim: Three work plan alternatives are investigated:

A) Performing minimum required repair on elements with $OBCI_{min} < 1$.

B) Improving approach elements to like-new, and performing minimum required repair on other elements with $OBCI_{min} < 1$.

C) Improving deck elements to like-new, and performing minimum required repair on other elements with $OBCI_{min} < 1$.

In addition to $OBCI_{current}$, BHI is also calculated at the bridge-level for these alternatives. For this purpose, weighting of condition-states vary linearly with respect to the average condition-state of elements. Element weight factors are also considered as the replacement cost of elements, which are used for the calculation of element-level OBCI.

For each alternative, the incurred agency costs, as well as the number of days required for performing such work plans are derived and presented in Table 4. According to this table, if the minimum required repair is performed on elements with $OBCI_{min} < 1$, $OBCI_{current}$ will be improved by 4%. It should be noted that under this work plan, the bridge will become structurally safe and operationally serviceable since condition-states of all elements will be above the minimum allowable thresholds. If the agency decides to spend more to achieve a better performance for this bridge, alternatives B and C can be chosen. According to Table 2 and Table 3, the elements within approach and deck components have the lowest condition-states and OBCI values. Thus, work plans B and C are suggested to primarily improve the condition-state of the elements within these components. In more details, alternative B is 63% more costly than work plan A, while the amount of improvement in OBCI following work plan B is only 3% more than work plan A. If the budget constraint allows, the responsible agency may spend $233,620 on work plan C to achieve an OBCI value as large as 0.966. The required time of performing this project is almost the same as work plan B (i.e. 12 days for work plans B and 13 days for work plan C). The cost of work plan C is $21,000 more than work plan B, while the increase in the OBCI value after performing work plan C is just 2% more than the increase in OBCI under work plan B, when they are compared to the OBCI value after performing merely minimum required repairs (i.e. work plan A). Thus, if the agency decides to select between work plans B and C, comparing the incurred costs, the required time, and the OBCI after executing these alternatives, work plan B may seem to be a better option. Results also show that, while OBCI indicates 6% and 8% improvement in the bridge performance following work plans B and C, BHI of the bridge is improved by only 1.80%. This can be mostly attributed to the fact that BHI considers healthy elements as those with all portions in condition-state 1. However, for steel and concrete elements, any improving action other than replacement, improves the state of defected portions of those elements to condition-state 2 (*16*). According to OBCI, these portions are considered to be in the like-new state, whereas BHI considers these portions in a state below the healthy state. As a result, BHI becomes insensitive to costly actions that maintain portions of these elements that are already in condition-state 2 (work plans B and C compared to work plan A). Furthermore, the required cost to improve condition-state of elements to their like-new state is not necessarily linearly proportionate to the total quantity of defected portions, which is the assumption in BHI. On the other hand, according to Table 4, OBCI is objectively able to reflect the amount of improvements achieved by costly MR&R actions.

Sensitivity of OBCI to Variations in ADT for the Case Study Bridge

A sensitivity analysis is performed to show the ability of the proposed OBCI in reflecting the effect of variations in serviceability parameters such as ADT on the performance of bridges. To this end, $OBCI_{current}$ is evaluated before and after performing work plan A considering four ADT values: 1) 50 vehicles/day (the original ADT of the bridge), and 2) 25%, 3) 50%, and 4) 75% of the bridge maximum traffic capacity (the maximum capacity of each lane is considered as 1,750 vehicles/lane/hour (*17*)). $OBCI_{current}$ is found as 0.90, 0.85, 0.78, and 0.51 for the bridge before conducting work plan A, and 0.93, 0.89, 0.86, and 0.63 after conducting work plan A. As these results show, $OBCI_{current}$ is sensitive to the variation of ADT, which affects the user cost of DVE. As the ADT values increase, the advert consequences on users become more significant compared to the agency costs of improving elements to their like-new state. Furthermore, as the user cost increases, the improvement in the OBCI following work plan A becomes more significant.

CONCLUSIONS

Ohio Bridge Condition Index (OBCI) is proposed as a reliable performance measure for bridges. This metric has the following features:

- Incorporates condition-state based direct and indirect consequences on users and the responsible agency.
- Evaluates the performance of bridges at element-, component-, bridge-, and network-levels.
- Reflects the negative effects of defects in bridge elements, as well as positive influences of taking improving actions on the condition index.

Given the objectives of bridge management by DOTs, two variations of OBCI are proposed. The first one is $OBCI_{min}$ which evaluates the proximity of the system to minimum acceptable conditions for its constituent elements. The user and agency costs of implementing repair actions on system elements that do not meet the minimum condition-state thresholds are compared with the user and agency costs of replacing the system. $OBCI_{min}$ ranges from 0 to 1, with 0 indicating that the system is in such a severe condition that replacement of the system incurs the least user and agency costs compared to other repair alternatives, in order to have all bridge elements meet their minimum condition-state thresholds. On the contrary, $OBCI_{min}$ with the value of 1 implies that all of the system elements have acceptable condition-states. The other formulation of OBCI is $OBCI_{current}$ which compares the current condition to the like-new condition of the system. $OBCI_{current}$ ranges from 0 to 1; bridges with healthier elements will have $OBCI_{current}$ closer to 1. A unique feature of OBCI is that it properly incorporates a comprehensive list of user and agency costs that are incurred as a consequence of performing repair/replacement actions. These costs include; agency cost of administration, engineering and mobilization; agency cost of performing repair/replacement actions; agency cost of maintenance of traffic; user cost incurred from delay time; vehicle operation, and excess emission; and user costs incurred from load and clearance restrictions.

The applications of the proposed indices are demonstrated for a case study bridge in Ohio. The inspection report, as well as information regarding configuration, type and the traffic flow of this bridge are provided by ODOT. The calculated $OBCI_{min}$ for this bridge shows that approach slab and embankment, and deck wearing surface, railing, drainage, and expansion joints require immediate repair. In line with that observation, element-level $OBCI_{current}$ indicates that approach and deck components have the worst conditions. These components also contribute the most to the required costs for the bridge to be improved to the like-new condition. Three work plan alternatives are suggested and discussed. Comparing the incurred costs (the required time) and the OBCI value after the application of these alternatives, the best work plans are suggested. Furthermore, it is found that Bridge Health Index (BHI), which is a conventional performance measure being used for management of bridges by many state DOTs, may not be an appropriate metric as it does not properly reflect effects of MR&R actions on the performance of bridges. Finally, the results show that $OBCI_{current}$ is reasonably sensitive to the variation of Average Daily Traffic (ADT), indicating the ability of the proposed index to reflect effects of ADT as a significant serviceability feature of bridges. Based on the capabilities provided by $OBCI_{min}$ and $OBCI_{current}$, these metrics can assist in proper maintenance of transportation systems and effective enhancement of their efficiency, safety, and capacity.

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TABLE 3 - Element-, component-, and bridge-level OBCI for the case study bridge

Bridge Element	$\mathrm{OBCI}_{\mathrm{min}}$			$\mathrm{OBCI}_{\mathrm{current}}$		
	Element	**Component**	**Bridge**	**Element**	**Component**	**Bridge**
Approach Items			0.95			0.90
Approach Wearing Surface	1.00	0.78		0.56	0.57	
Approach Slab	0.62			0.42		
Embankment	0.00			0.00		
Guardrail	1.00			1.00		
Deck Items						
Floor/Slab	1.00	0.90		0.98	0.82	
Wearing Surface	0.76			0.58		
Curb/Sidewalk/Walkway	1.00			0.87		
Railing	0.93			0.86		
Drainage	0.56			0.56		
Expansion Joint	0.70			0.70		
Superstructure Items						
Beams/Girders	1.00	1.00		0.96	0.99	
Bearing Device	1.00			1.00		
Substructure Items						
Abutment Walls	1.00	1.00		0.97	0.99	
Pier Caps	1.00			0.97		
Pier Columns/Bents	1.00			1.00		
Wingwalls	1.00			1.00		
Scour	1.00			1.00		
Slope Protection	1.00			1.00		
Channel Items						
Alignment	1.00	1.00		1.00	1.00	
Protection	1.00			1.00		
Hydraulic Opening	1.00			1.00		
Sign Items						
Utilities	1.00	1.00		1.00	1.00	

TABLE 4 Proposed MR&R work plans for the case study bridge

Work Plan	Description	Agency cost of the work plan	Duration (days)	$\mathbf{OBCI_{curren}}$	BHI
0	Condition of the bridge after inspection	-	-	0.895	0.944
A	Perform minimum required repair on elements with $\mathbf{OBCI_{min}}$<1	$130,810	9	0.928	0.961
B	Improve approach elements to like-new, and perform minimum required repair on other elements with $\mathbf{OBCI_{min}}$<1	$212,800	12	0.951	0.961
C	Improve deck elements to like-new, and perform minimum required repair on other elements with $\mathbf{OBCI_{min}}$<1	$233,620	13	0.966	0.961

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