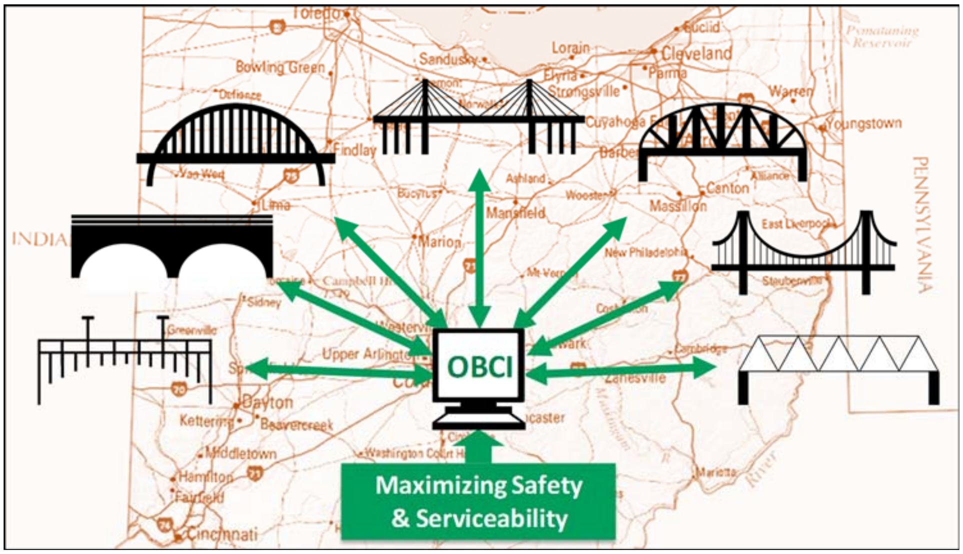
A Bridge Condition Index for Transportation Asset Management in Ohio



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16. Abstract

A comprehensive and practical performance measure, called Ohio Bridge Condition Index (OBCI), has been developed in this project. OBCI is a cost-based index that ranges from zero to one and represents the performance of bridges at element-, component-, bridge-, and network-levels. The index effectively uses ODOT's bridge inventory and inspection databases. Effects of serviceability and safety features of bridges are objectively incorporated in this index through a broad set of direct and indirect consequences of various bridge conditions. Based on this novel index and implementing a mixed-integer linear programing technique, a systematic optimal budget allocation algorithm is developed that identifies the optimal Maintenance, Repair, and Replacement (MR&R) work plans for National Highway System (NHS) bridges of ODOT's districts for available budgets.

Application of the proposed index to numerous Ohio bridges show that OBCI not only reflects the impacts of structural deficiencies, but also the adverse consequences imposed on users due to repair actions. It is also demonstrated that OBCI can effectively identify bridges with safety concerns and estimate bridge repair costs for various target performances. Furthermore, through the application of the optimization algorithm for the 484 NHS bridges in District 3, it is shown that the algorithm systematically assigns higher priority to work plans that reduce safety risks of bridges, and to bridges with high traffic demand and long detour length to enhance their serviceability.

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Executive Summary

The most recent estimates put the nation's backlog of bridge rehabilitation needs at $123 billion, highlighting the need for effective management of these critical assets. Ohio has the second largest portfolio of bridges in the nation. These structures, that are diverse in type, configuration and age, are spread over the state and are exposed to various environmental conditions and traffic loadings. Such factors pose a major challenge for performance evaluation and subsequently management of bridges in Ohio. Various bridge performance indices have been developed and implemented by state DOTs, FHWA, NCHRP, and other entities as critical tools for management of large portfolios of bridges in transportation systems. However, in these indices either major safety and serviceability consequences are neglected, or subjective weight factors are considered to account for such consequences. Subsequently, these indices may offer unrealistic or subjective representation of the performance of bridges, which may result in improper repair and preservation strategies.

In collaboration with Ohio Department of Transportation (ODOT), an objective, comprehensive and practical performance measure, called Ohio Bridge Condition Index (OBCI), is developed in this project. This metric effectively utilizes ODOT's bridge inventory and inspection databases. OBCI is a cost-based index that ranges from zero to one and represents the performance of bridges at element-, component-, bridge-, and network-levels. Effects of serviceability and safety features of bridges are incorporated in this index through a broad set of direct and indirect consequences of various bridge conditions using the unified metric of cost. Three variations of OBCI are developed including $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$. In $OBCI_{min}$ the proximity of the system to minimum acceptable conditions for its constituent elements is evaluated. 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. $OBCI_{current}$ compares the current condition of the system to its like-new condition. Similarly the costs to improve all elements of the system to their like-new state is compared with the incurred cost for replacing the system. With the performance objective of reaching like-new state, $OBCI_{current(risk-based)}$ quantitatively accounts for safety risks associated with severity, extent, location, and pattern of defects for major bridge elements.

OBCI is first applied to a number of Ohio bridges. Results show that the index not only reflects the impacts of structural deficiencies, but also the adverse consequences imposed on users due to repair actions. Additionally, to examine the efficiency of the OBCI, the results are compared to Bridge Health Index (BHI), which is a common bridge performance metric. It is found that BHI may not be an appropriate metric as it does not properly reflect effects of Maintenance, Repair, and Replacement (MR&R) actions on the performance of bridges. The application of the three variations of OBCI is also demonstrated for identifying bridges with safety concerns, estimating bridge repair costs, and assisting in bridge management decision-making.

Facilitated by the development of a module-based computer program in this project, cost and OBCI values are calculated for the entire 228 National Highway System (NHS) bridges in district 10 of Ohio. Based on the data from 2017, the required agency cost, as well as the incurred user and agency costs to improve all bridges to the minimum acceptable conditions, as well as their like-new states, are separately calculated. Furthermore, $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ for the network of bridges in this district are computed as 0.835, 0.666, and 0.649, respectively. Similar cost and OBCI analyses are performed at bridge- and component-level, as well. These results show that around 50% of bridges are at their minimum acceptable conditions. Additionally, based on the results of $OBCI_{current(risk-based)}$, which includes safety risks in addition to other costs, culverts with around 30% and substructures with around 80% having $OBCI_{current(risk-based)} \geq 0.9$ are found to be the most critical and the safest among components in the inventory, respectively.

Based on this novel index and implementing mixed-integer linear programing technique, a systematic optimal budget allocation algorithm is developed that identifies the optimal MR&R work plans for NHS bridges in ODOT's districts. Considering the limitations in the available budget, this algorithm determines optimal actions at element-level such that the network-level OBCI performance of districts is maximized.

As demonstrated in this report, this objective is equivalent to minimizing annual safety risks of bridges and the serviceability interruptions on users due to repair actions on these assets.

Through a developed computer program, the optimization framework is employed for identifying optimal MR&R actions for the 484 NHS bridges in district 3 of Ohio considering a maximum budget of $14,350,000. Based on the data from 2017, the optimization algorithm determines 109 bridges to receive MR&R actions. According to these results, around 40% of the district budget is recommended for MR&R actions on steel protective coatings. Furthermore, 52 bridges among 109 bridges receiving MR&R action budgets are found requiring MR&R actions for their reinforced concrete abutments. Finally, through several verification and validation tests, the ability of the algorithm to systematically assign higher priority to work plans that reduce safety risks of bridges, and to bridges with high ADT and long detour length are demonstrated.

OBCI objectively integrates a comprehensive list of consequences associated with bridge management. As supported by the results, the three variations of OBCI, i.e. $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$, can be utilized to identify bridges with safety concerns, estimating bridge repair costs for various target performances, and assisting in identifying appropriate repair alternatives for bridge management decision-making. Additionally, ODOT and other state DOTs can benefit from OBCI for an objective and refined evaluation of the performance of their large bridge portfolios; features that are not provided by General Appraisal (GA), which is a commonly applied performance measure. This distinctive attribute of OBCI not only facilitates effective communications about bridge conditions with the public, but also assists responsible agencies with planning for their bridges or bridge components in large portfolios to achieve target performance objectives.

In light of budget limits, ODOT districts and other state DOTs can take advantage of the developed budget allocation program to systematically identify optimal MR&R actions for their bridges such that the safety and serviceability, and in general, the performance of their bridge portfolios are maximized. A graphical software application for this optimal budget allocation framework is developed, which enables a user-friendly interaction with the computer program for bridge engineers and decision-makers.

1. 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 Maintenance, Repair, and Replacement (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, legislatures, 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, published in (2) and elaborated in Appendix A, were proposed/implemented by state DOTs, FHWA, NCHRP, and other researchers. In many indices such as SR (3) and DR (4), subjective weight factors are considered to account for structural and serviceability improper functionalities, whereas in reality, the likelihood of these adverse events, 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 (5–7). 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 report presents a novel cost- and risk-based performance metric called Ohio Bridge Condition Index (OBCI). The considered costs include two categories. (1) Implementation costs referring to costs of applying upgrades or repair actions. An important feature of the proposed index is the incorporation of a comprehensive list of incurred costs to reliably determine consequences of such repair/upgrade actions. (2) Structural/serviceability costs of bridge improper functionality referring to the costs of consequences as a result of potential improper functionality of bridges, which depends on the severity of the existing condition of these bridges.

In light of budget limitations, OBCI, as an objective index, can be directly utilized for prioritizing MR&R actions on bridges. For this purpose, an optimization framework based on an integer programing algorithm is proposed that considers budget limitations. The objective in this framework is to maximize the OBCI of a selected portfolio of bridges, or equivalently, minimize structural risks and serviceability interruptions to reach the like-new state for these bridges.

In the rest of this report, the scope of the OBCI is presented, the involved cost terms are explained, minimum safe and serviceable thresholds for the condition-state of bridge elements are introduced, formulations of three versions of OBCI are developed, the proposed OBCI formulations are applied to case study bridges from ODOT`s bridge inventory, a framework based on OBCI for optimal budget allocation with budget constraints is proposed, a module-based computer program and a graphical application is developed for cost and OBCI calculation and optimal budget allocation, application of OBCI and optimal budget allocation is shown for National Highway System (NHS) bridges in district 10 and 3 of Ohio, and finally, in-depth studies are conducted for the validation and verification of the optimal budget allocation algorithm.

2. 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 improper functionality 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:

1) Implementation costs: 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 (AEM), maintenance of traffic (MOT), and costs of executing MR&R actions on bridge elements (MR&R). 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 delay time on users, extra vehicle operation, and excess emission (DVE). Systematic methods for the calculation of the implementation costs are developed in this research, published in (8), and presented in Appendix B. Additionally, these detailed cost formulations have assisted researchers in the field of bridge management to evaluate the lifecycle cost of bridge assets more accurately and suggest more reliable hazard mitigation plans (e.g. (9–11)).

2) Structural/Operational cost of bridge improper functionality: 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 improper functionalities may occur. Thus, the quantification of consequent improper functionality in terms of monetary units helps responsible agencies with the decision-making process through cost-benefit analyses. In addition, bridge improper functionality has a likelihood of occurrence, which depends on the severity of the bridge health condition. Thus, for the purpose of quantifying the adverse consequences of such potential improper functionalities, the concept of risk, i.e. the product of the likelihood and the consequent costs of structural/serviceability improper functionality, can be applied in OBCI. These costs of consequences are expected costs due to improper functionality in the structural/ serviceability performance of bridges that can potentially occur as a result of deterioration, fatigue, flooding and scour, among other factors. When a disruption in the bridge functionality occurs, both users and agencies are affected. The responsible agency repairs the damaged elements. Thus, all of the cost terms of the agency and user costs that were mentioned for the implementation costs, should be considered for the “structural/Operational cost of bridge improper functionality”.

2.1 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 (12), ODOT provides an overall condition-state rating for elements in a scale from 1 to 4 (13). 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 associated with specific bridge elements.

- 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 (12) and ODOT (13), 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, three versions of the OBCI are presented and the application of these indices are demonstrated for ODOT`s bridges.

2.2 OBCI models

Effectively utilizing ODOT's bridge inventory and inspection databases, based on the most recent AASHTO condition-state rating system (12,13), three OBCI models are suggested and developed in this report: $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ (2,14,15). In each of these variations, performance of the system is compared with a target performance for that member in terms of cost, as follows:

$$OBCI = 1 - \frac{\sum cost\ to\ meet\ the\ target\ state(\$)}{replacement\ cost(\$)} \tag{2-1}$$

where *replacement cost* is the cost to meet the target state when the system is in the worst condition (most costly scenario). On this basis, OBCI varies from 0 (worst performance) to 1 (best performance like a new bridge). Unlike other metrics, OBCI objectively represents the proximity of the system to meet the target state. Based on structural and serviceability features of the system and inspection report, an action plan is identified to improve the member to the target state. Then, the total agency and user costs associated with this action plan are calculated and inserted in the numerator of the OBCI formula in Equation (2-1). The incurred total agency and user costs for replacing the system is also calculated and inserted in the denominator of Equation (2-1). Having computed these two cost terms, OBCI of the system can be derived following Equation (2-1). A general flowchart of the OBCI calculation is also presented in Figure 2-1. In the following subsections, each of the three indexes are elaborated and discussed.

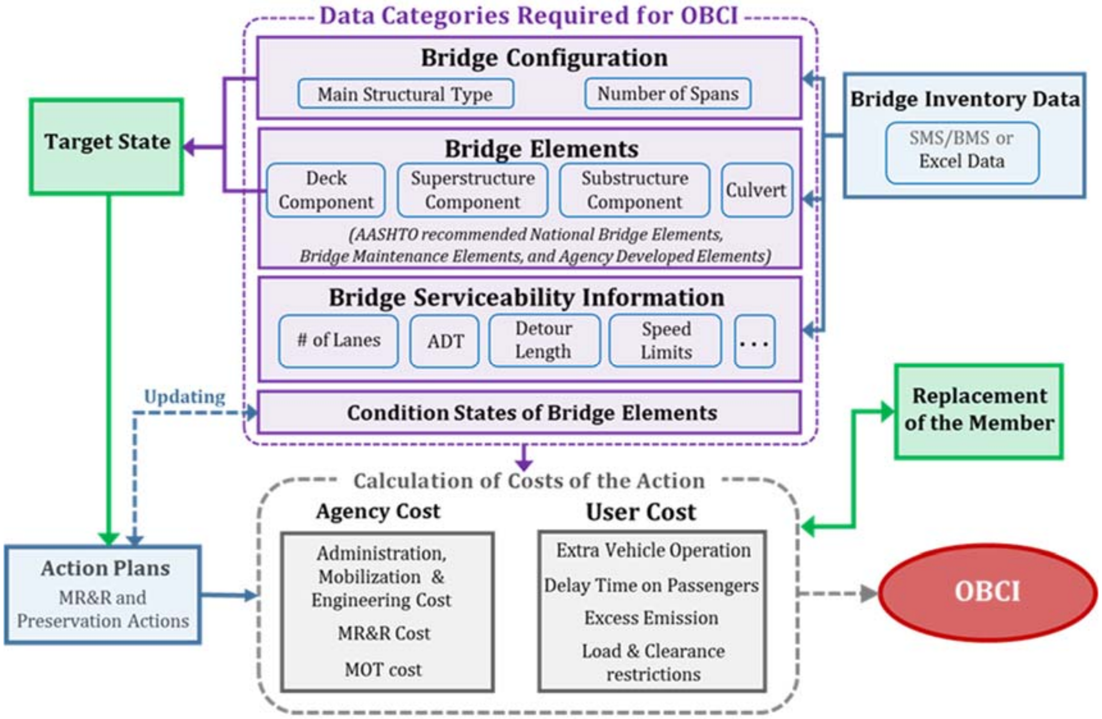


Figure 2-1- General flowchart of the proposed OBCI with minimum condition-state thresholds

2.2.1 $OBCI_{min}$

In $OBCI_{min}$, the performance objective is that the condition-states of all bridge elements exceed their minimum safety and serviceability thresholds. In line with the most recent AASHTO recommended condition-state rating system, at element-level, in consultation with ODOT structure team, authors have defined the following minimum thresholds:

- The percentage of NBE, defects associated with specific bridge elements, and primary 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%.

These conditions are expected to assure a minimum level of safety and serviceability for bridge members. On this basis, $OBCI_{min}$ for a bridge member is presented as a comparison between the incurred costs as a result of improving the condition-state of the constituent elements to just above their minimum thresholds, and the incurred costs to replace such members. In this context, $OBCI_{min}$ is calculated as follows:

$$OBCI_{min}^{l} = 1 - \frac{AC_l^{min} + UC_l^{min}}{AC_l^{rep} + UC_l^{rep}} \tag{2-2}$$

where l is the level for which OBCI is evaluated. As mentioned in Section 2.1, there are element-, component-, bridge-, and network-levels. The terms AC_l^{min} and UC_s^{min} are the incurred agency and user costs as a result of enhancing condition-state of the constituent elements to just above their minimum thresholds. A comprehensive list of such agency and user costs are considered in this research and provided in Appendix B. On this basis, Equation (2-2) can be expanded as:

$$OBCI_{min}^{l} = 1 - \frac{MR\&R_l^{min} + MOT_l^{min} + AEM_l^{min} + DVE_l^{min}}{MR\&R_l^{rep} + MOT_l^{rep} + AEM_l^{rep} + DVE_l^{rep}} \tag{2-3}$$

where $MR\&R_l^{min}$, MOT_l^{min}, and AEM_l^{min} are the agency costs of maintenance, repair and replacement, maintenance of traffic, and administration, engineering, and mobilization to improve the condition-state of the constituent elements of member l to their minimum safe and serviceable state. The term DVE_l^{min} indicates the incurred user cost of delay time, extra vehicle operation, and excess gas emission as a result of performing MR&R actions to improve member l to the minimum safe and serviceable state. As mentioned, in Appendix B, systematic procedures for the calculation of these costs for any level of interest are provided.

In general, some of the features provided by $OBCI_{min}$ can be mentioned as follows:

- $OBCI_{min}$ evaluates the proximity of the system to the 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).

2.2.2 $\boldsymbol{OBCI_{current}}$

In $OBCI_{current}$, the performance objective is that all elements of the system are at their desired like-new state. In consultation with ODOT structure team, the like-new state is defined as:

- Portions of the element in condition-states 3 and 4 should be repaired to improve to at least condition-state 2.

- Portions of the element in condition-state 2 should be maintained to stay in that condition-state.

Similar to $OBCI_{min}$, a set of actions that are required to improve all elements of the system to their like-new state is first identified. Then, the user and agency costs associated with these actions are calculated and compared with the incurred user and agency costs for replacing that member. Similar to Equation (2-3), $OBCI_{current}$ can be mathematically calculated as follows:

$$OBCI_{current}^{l} = 1 - \frac{MR\&R_l^{ln} + MOT_l^{ln} + AEM_l^{ln} + DVE_l^{ln}}{MR\&R_l^{rep} + MOT_l^{rep} + AEM_l^{rep} + DVE_l^{rep}} \tag{2-4}$$

where the superscript ln represents the target like-new state of the system. As can be seen, $OBCI_{current}$ compares the current condition of the system with the like-new condition to indicate how close the system is to its desirable conditions.

2.2.3 $\boldsymbol{OBCI_{current(risk-based)}}$

For major elements that are in the load path of bridges, severity, extent, location, and pattern of defects may raise safety concerns for the entire bridge. Thus, a third variation of OBCI is developed that objectively accounts for such safety concerns in terms of the annual risk of improper functionality. In this OBCI model, the performance objective is identical to that of $OBCI_{current}$. Considering the safety of a bridge member that contains at least one major element, there are two possible scenarios within one year inspection interval:

1) The member functions properly. Thus, to reach the like-new state of the member at the end of this one year, MR&R actions need to be scheduled (if the conditions of the elements of the

member are worse than their like-new state). These actions are accompanied with incurred agency and user costs of MR&R, MOT, AEM, and DVE. Thus, the risk cost corresponding to this scenario is the probability that the system functions properly (i.e. $\left(1-P_l^f\right)$ with P_l^f as the annual probability of improper functionality of the member at level l), times the incurred agency and user costs to perform required MR&R actions to improve elements of the member to their like-new state (i.e. $(AC_l^{ln}+UC_l^{ln})$).

2) The member fails to function properly. In this case, the entire bridge is considered to be replaced as the consequence of that improper functionality. Thus, the risk cost corresponding to this scenario is the product of the probability of improper functionality of the member and the incurred user and agency costs as a result of the replacement of the entire bridge (i.e. $(AC_B^{rep}+UC_B^{rep})$).

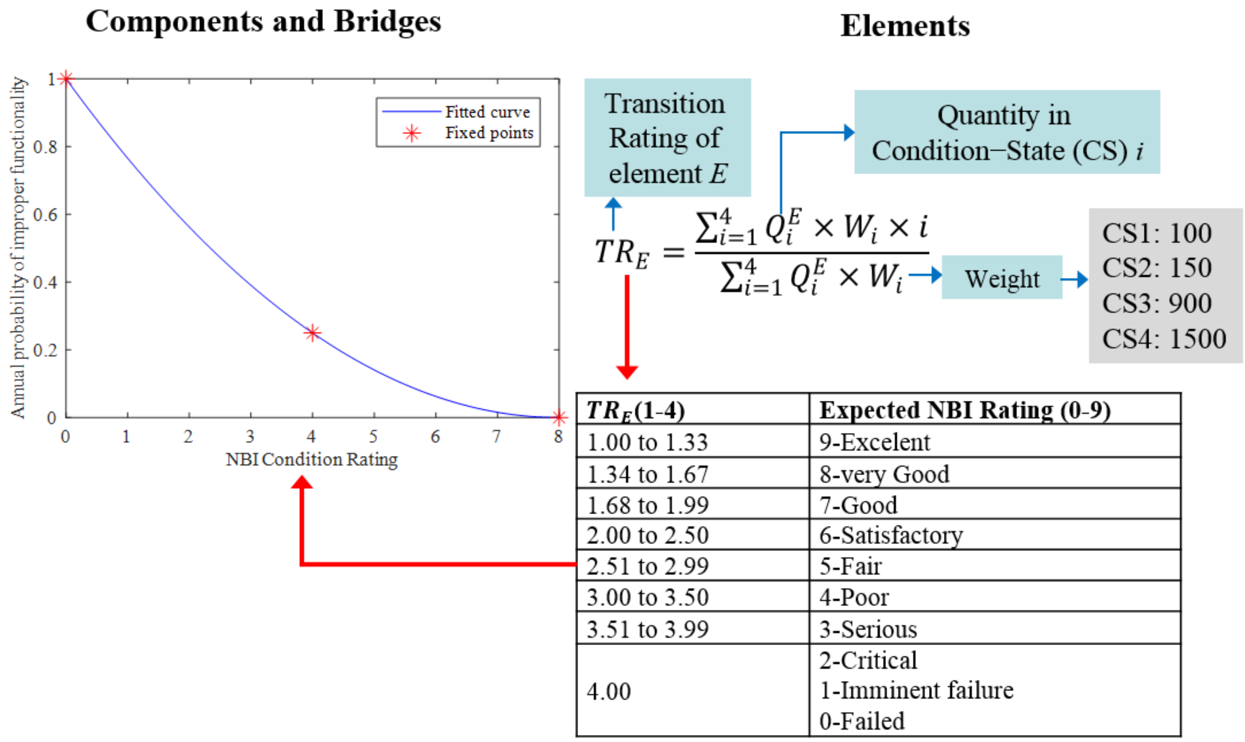
In $OBCI_{current\ (risk-based)}$, the above risk costs are compared with similar risk costs, when the member is planned to be replaced at the end of the year. On this basis, the mathematical formulation of $OBCI_{current\ (risk-based)}$ for a member at level l, i.e. element-, component-, bridge-, and network-levels, is proposed as follows:

$$OBCI^{l}_{current(risk-based)}=1-\frac{\left(1-P_l^f\right)\times(AC_l^{ln}+UC_l^{ln})+P_l^f\times(AC_B^{rep}+UC_B^{rep})}{\left(1-P_l^f\right)\times(AC_l^{rep}+UC_l^{rep})+P_l^f\times(AC_B^{rep}+UC_B^{rep})} \tag{2-5}$$

According to Equation (2-5), a member in its like-new state, which does not have any safety concerns, has an $OBCI_{current(risk-based)}$ of one, whereas a major member in its worst condition has an $OBCI_{current(risk-based)}$ of zero. Authors have suggested a second-order polynomial function to approximately estimate P^f for components and bridges based on their NBI summary ratings and NBI general appraisals, respectively (see Figure 2-2). To this end, three fixed points including (0,1), (4,0.25), and (8,3.10e-6) are used to solve for the coefficient of this second order polynomial function. These points are considered based on the following reasoning:

- According to AASHTO LRFD bridge design specification (16) and Swanson and Miller (17), annual rate of improper functionality for NBI rating of 8 for substructure/superstructure components is 3.1e-6. The same values are considered for culvert and channel components.
- According to the descriptions of NBI rating (3), failed condition occurs at NBI rating of 0.
- According to the descriptions of NBI rating (3), a component/bridge in poor condition with advanced damage has approximately 25% chance of improper functionality.

For major elements, according to ODOT (18), transition ratings are calculated as a weighted average over the portions of an element in condition-states 1 to 4. Then, based on the estimation of ODOT (18), equivalent NBI ratings can be suggested for those transition ratings, which can be subsequently used for the calculation of probabilities of improper functionality. These procedures are illustrated in Figure 2-2.



$$TR_E = \frac{\sum_{i=1}^{4} Q_i^E \times W_i \times i}{\sum_{i=1}^{4} Q_i^E \times W_i}$$

TR_E(1-4)	Expected NBI Rating (0-9)
1.00 to 1.33	9-Excelent
1.34 to 1.67	8-very Good
1.68 to 1.99	7-Good
2.00 to 2.50	6-Satisfactory
2.51 to 2.99	5-Fair
3.00 to 3.50	4-Poor
3.51 to 3.99	3-Serious
4.00	2-Critical 1-Imminent failure 0-Failed

Note: CS=Condition-state

Figure 2-2- A framework for the calculation of the probability of improper functionalities for major elements, components, and bridges

2.3 Case study numerical calculations

Actual Ohio bridges are selected to evaluate the three variations of the proposed OBCI. This section includes two case studies. In the first investigation, $OBCI_{min}$ and $OBCI_{current}$ of a sample Ohio bridge are calculated at element-, component-, and bridge-levels and the results are discussed. Moreover, a number of optimal repair plans are suggested accordingly, the calculated OBCI values are compared with the BHI, which is a commonly utilized index, and the sensitivity of OBCI is evaluated with respect to a bridge serviceability feature. In the second case study, the capability of $OBCI_{current(risk-based)}$ to identify bridges with safety concerns, which require prioritized repairs, is demonstrated for two sample Ohio bridges. Furthermore, the new capabilities offered by the application of all three versions of OBCI for assisting in decision-making of these bridges is demonstrated.

2.3.1 Case study 1

For the demonstration of $OBCI_{min}$ and $OBCI_{current}$, 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 2-1 presents the inspection data for this bridge including the quantity of elements in the four available condition-states.

Table 2-1- 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	0
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

2.3.1.1 Calculation and evaluation of $OBCI_{min}$ and $OBCI_{current}$

As explained in Appendix B, element-, component-, and bridge-level information is required for the calculation of OBCI. 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 elements 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, sealing the defected cracked area of the concrete deck with condition-state 2 costs $2.22/ft^2 and maintains these areas in 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, and number of lanes 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 (see Appendix B), 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.

- 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. These factors are considered to be 0.80, and 0.90, for component-, and bridge-levels, respectively.

- The replacement cost of the bridge is extracted from Caltrans (19). 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 (20) are used.

Based on the aforementioned information and systematic formulations presented in Appendix B, 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 (2-3) and (2-4), and the results are provided in Table 2-2. As seen, OBCI is not provided for the “alignment” of superstructure component. According to ODOT inspection manual (13) and AASHTO manual for bridge inspection (21), 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, which can be a topic of future research.

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 may require prioritized 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. Additionally, the index shows this cost is just 5% of the total replacement cost of the bridge, i.e. $(1-0.95) \times Replacement\ cost$. Based on Equation (2-3), 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 2-2 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 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 2-2- Element-, component-, and bridge-level OBCI for the case study bridge

OBCI	$OBCI_{min}$	$OBCI_{current}$
Bridge-level		
Case Study Bridge	0.95	0.90
Component-level		
Approach	0.78	0.57
Deck	0.90	0.82
Superstructure	1.00	0.99
Substructure	1.00	0.99
Channel	1.00	1.00
Sign	1.00	1.00
Element-level		
Approach Wearing Surface	1.00	0.56
Approach Slab	0.62	0.42
Embankment	0.00	0.00
Guardrail	1.00	1.00
Floor/Slab	1.00	0.98
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
Beams/Girders	1.00	0.96
Bearing Device	1.00	1.00
Abutment Walls	1.00	0.97
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
Alignment	1.00	1.00
Protection	1.00	1.00
Hydraulic Opening	1.00	1.00
Utilities	1.00	1.00

2.3.1.2 Comparison of OBCI with BHI

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 2-3. 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 2-1 and Table 2-2, 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 (22). 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 2-3, OBCI is objectively able to reflect the amount of improvements achieved by costly MR&R actions.

Table 2-3- Proposed MR&R work plans for the case study bridge

Work Plan	Description	Agency cost of the work plan	Duration (days)	$OBCI_{current}$	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

2.3.1.3 Sensitivity of OBCI to the variations of traffic demand

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 (23)). $OBCI_{current}$ 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 adverse 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.

2.3.2 Case study 2

Two real bridges in Ohio are considered for the demonstration of the benefits that $OBCI_{current(risk-based)}$ provides for the identification of safety-critical bridge members, as well as the application of the three variations of OBCI for assisting in optimal bridge decision-making. These bridges are the I-480 E.B. Over Cuyahoga River-Ohio Canal bridge and the SR 4 north CSX RR bridge. The former is a 15 spans steel girder bridge with a total deck area of 303,315 ft^2 supporting four traffic lanes with an average daily traffic of 72,870. The latter is a 16 spans prestressed concrete box-beam bridge with a total deck area of 27,394 ft^2 supporting two traffic lanes with an average daily traffic of 34,547 vehicles.

2.3.2.1 Identification of safety-critical bridges using $\boldsymbol{OBCI_{current(risk-based)}}$

In the I-480 E.B. Over Cuyahoga River-Ohio Canal bridge, the summary rating for the deck component is recorded as 5 in the 9-0 scale (see Figure 2-3), which represents a critical condition. According to this inspection sheet, the only element affecting the summary rating of the deck component is “Floor/Slab” (13). This element from the deck component is in the load path of the bridge. Calculations show that this element has an $OBCI_{min}$ of 1.000 (see Table 2-4), i.e. the element is structurally/operationally acceptable in terms of satisfying the defined minimum condition-state threshold. On this basis, considering severity and extent of damage, this element does not require immediate repair. However, according to the summary rating of 5 that is assigned by the inspector, one expects that immediate MR&R actions may be warranted for the bridge. Based on the defects described in the inspection sheet, the inspector is concerned about the 9.2% of the deck underside having defects of various types, including spalling, scaling and exposed reinforcements. Furthermore, in the inspection report, the inspector warns about sub-decking in spans 8 and 9 of this bridge. On this basis, the bridge seems to be vulnerable to improperly function in these two spans. This issue, as well as the 9.2% of the underside deck being defected, have resulted in the summary rating of 5 for the deck component.

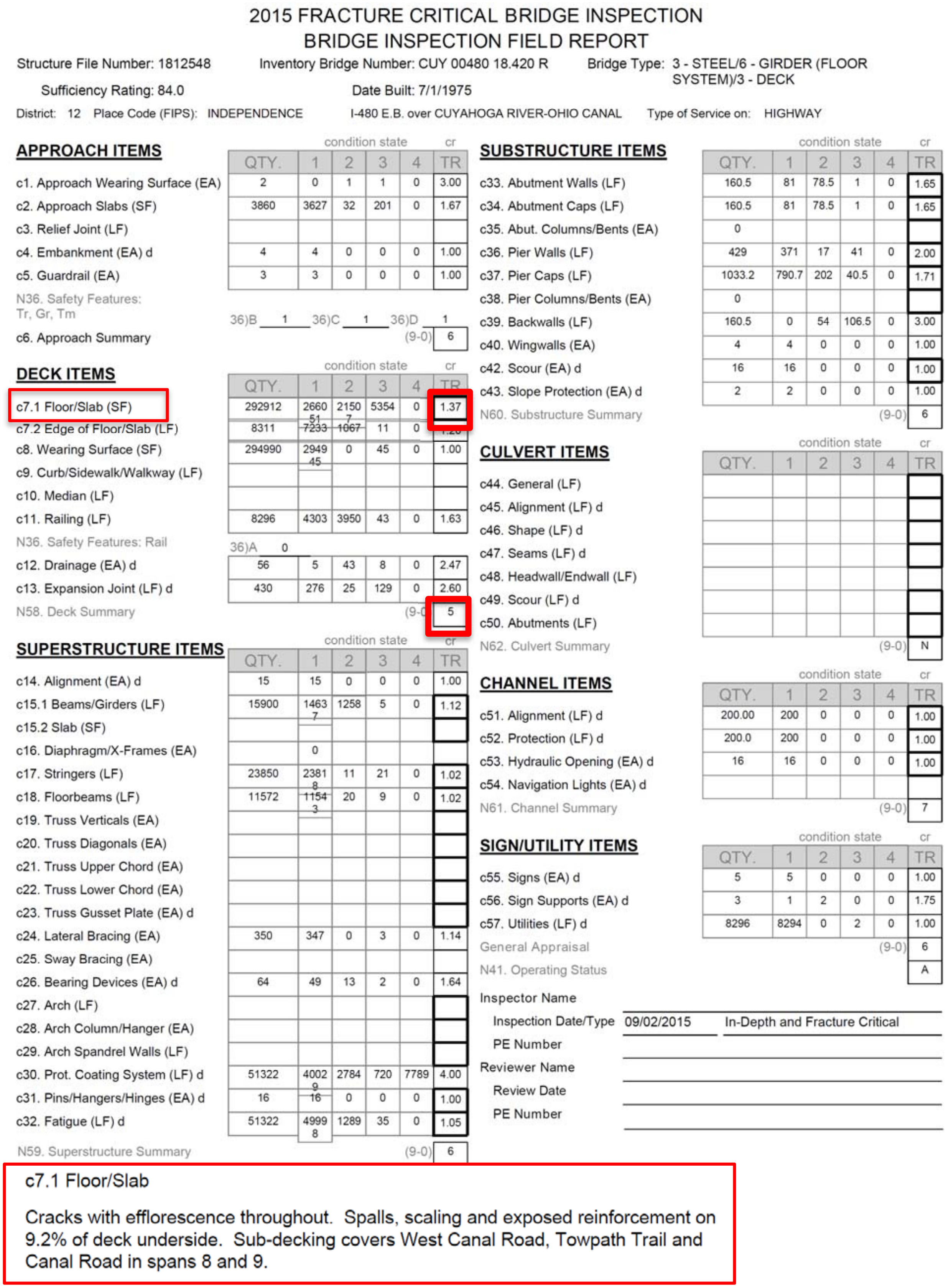
In the SR 4 North Over CSX RR, according to the inspection report of this bridge in year 2015 (provided in Figure 2-4), the summary ratings for all components of this bridge were greater than 7, except for the substructure. In spite of all elements in this component having more than 87% in condition-state 1, 15% of pier caps was in condition-state 3. As a result, $OBCI_{min}$ and $OBCI_{currernt}$ of the pier caps element is calculated as 0.862 and 0.728, respectively (see Table 2-5). These values, however, do not properly reflect the criticality of the defects, since according to the inspection report, the entire length of pier cap 7 is observed to have spalls with exposed rebar and vertical and horizontal cracks. This shows that the majority of the defects to the pier caps element is localized in just one cap (out of 14 caps), and that the bridge is vulnerable to improperly function at a local structural level.

Despite all the advantages provided by $OBCI_{min}$ and $OBCI_{current}$, the foregoing limitations motivated development of $OBCI_{current(risk-based)}$, in which safety risks are directly reflected in the performance index of bridge members. In this section, associated $OBCI_{current(risk-based)}$ for element-, component- and bridge levels associated with the foregoing defected major elements of the I-480 E.B. Over Cuyahoga River-Ohio Canal bridge and the SR 4 North Over CSX RR bridge are calculated and presented separately in Table 2-6. These values are also compared with corresponding values for $OBCI_{current}$, which does not reflect the effect of safety concerns of elements. Results show that $OBCI_{current(risk-based)}$ successfully represents safety concerns of these elements by showing relatively low values, whereas these effects are not shown in the $OBCI_{current}$ of these members. The results also show that the importance of safety concerns in the index slightly diminishes as $OBCI_{current(risk-based)}$ is calculated for larger scale members, i.e. for component- and bridge-levels. This is due to the fact that the risk cost of replacing the members (the terms in the denominator of Equation (2-5)) increases more than the cost of improving the member to its like-new state (the terms in the numerator of Equation (2-5)) as the scale increases.

A comparison is also made among $OBCI_{min}$, $OBCI_{current}$ and $OBCI_{current(risk-based)}$ for the entire elements and components of the two sample bridges. These results are shown in Table 2-4 and Table 2-5 of this study. Results indicate that for a number of elements other than the two critical elements with safety concerns, the $OBCI_{current(risk-based)}$ is small and distinctly different from $OBCI_{current}$. These elements are: beams/girders, pier walls, and pier caps of the I-480 E.B. Over Cuyahoga River-Ohio Canal bridge. In similar ways, safety-related concerns can be inferred from the descriptions of defects provided for these elements by the inspector. When the risk cost of improper functionality of an element is significantly larger than its replacement cost or the cost to improve these elements to their like-new state, $OBCI_{current(risk-based)}$ considerably decreases (see Equation (2-5)). For this reason, $OBCI_{current(risk-based)}$ of the pier walls element is calculated as low as 0.093. For this element, \$15M, \$1.9M, and \$0.25M are computed as the risk cost of improper functionality (which is the product of the probability of improper functionality of pier walls, i.e. 0.0625, and the replacement cost of the bridge, i.e. \$243M), replacement cost of the element, and the cost to improve this element to its like-new state, respectively.

2.3.2.2 Application of the three variations of OBCI for assisting in decision-making

As explained before, $OBCI_{min}$ is an indication of how close the member is to its minimum condition-state threshold. Those members that have an $OBCI_{min} < 1$ may have high priority of receiving corrective repair actions. On the other hand, $OBCI_{current}$ determines how far the member is to its like-new state. Since the difference between $OBCI_{min}$ and $OBCI_{current}$ values for most of the members of the two example bridges is small, the required cost to achieve like-new state is very close to the required cost for improving these members to just above their minimum required thresholds. Thus, agencies may decide to spend slightly more to improve these members to their like-new state. Then, to affirm safety of members, agencies may decide to observe $OBCI_{current(risk-based)}$ values. As justified before, due to the criticality of the location and/or pattern of defects in some elements, the difference between $OBCI_{current}$ and $OBCI_{current(risk-based)}$ is large. This is the case for floor/slab, beams/girders, pier walls, and pier caps of the I-480 E.B. Over Cuyahoga River-Ohio Canal bridge and the pier caps of the SR 4 north CSX RR bridge. This indicates that while these elements may have an overall healthy condition, they suffer from localized defects that may threat the safety of these members and the bridges. Due to high consequences of improper functionality of these members, agencies may decide to perform repairs on these elements immediately, despite their overall healthy condition. The required user and agency costs of improving these members can be directly compared with their replacement costs through $OBCI_{current}$; since one minus this index is the ratio of the incurred costs to improve the member to its like-new state, to the incurred costs of replacing that member (see Equation (2-4)). Based on this information, agencies may more efficiently decide between replacing and repairing bridge members. As an example, despite the low $OBCI_{current(risk-based)}$value of the pier walls element of the I-480 E.B. Over Cuyahoga River-Ohio Canal bridge (which is as low as 0.093), agencies may decide to just repair this element, as according to the $OBCI_{current}$ of this element, the user and agency-incurred costs for this action is just 13% of the replacement costs of this element.



2015 FRACTURE CRITICAL BRIDGE INSPECTION
BRIDGE INSPECTION FIELD REPORT

Structure File Number: 1812548 Inventory Bridge Number: CUY 00480 18.420 R Bridge Type: 3 - STEEL/6 - GIRDER (FLOOR SYSTEM)/3 - DECK

Sufficiency Rating: 84.0 Date Built: 7/1/1975

District: 12 Place Code (FIPS): INDEPENDENCE I-480 E.B. over CUYAHOGA RIVER-OHIO CANAL Type of Service on: HIGHWAY

APPROACH ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c1. Approach Wearing Surface (EA)	2	0	1	1	0	3.00
c2. Approach Slabs (SF)	3860	3627	32	201	0	1.67
c3. Relief Joint (LF)						
c4. Embankment (EA) d	4	4	0	0	0	1.00
c5. Guardrail (EA)	3	3	0	0	0	1.00

N36. Safety Features: Tr, Gr, Tm 36)B 1 36)C 1 36)D 1

c6. Approach Summary (9-0) 6

DECK ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c7.1 Floor/Slab (SF)	292912	266051	21507	5354	0	1.37
c7.2 Edge of Floor/Slab (LF)	8311	7233	1067	11	0	[illegible]
c8. Wearing Surface (SF)	294990	294945	0	45	0	1.00
c9. Curb/Sidewalk/Walkway (LF)						
c10. Median (LF)						
c11. Railing (LF)	8296	4303	3950	43	0	1.63
N36. Safety Features: Rail	36)A 0					
c12. Drainage (EA) d	56	5	43	8	0	2.47
c13. Expansion Joint (LF) d	430	276	25	129	0	2.60
N58. Deck Summary					(9-0)	5

SUPERSTRUCTURE ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c14. Alignment (EA) d	15	15	0	0	0	1.00
c15.1 Beams/Girders (LF)	15900	14637	1258	5	0	1.12
c15.2 Slab (SF)						
c16. Diaphragm/X-Frames (EA)		0				
c17. Stringers (LF)	23850	23818	11	21	0	1.02
c18. Floorbeams (LF)	11572	11543	20	9	0	1.02
c19. Truss Verticals (EA)						
c20. Truss Diagonals (EA)						
c21. Truss Upper Chord (EA)						
c22. Truss Lower Chord (EA)						
c23. Truss Gusset Plate (EA) d						
c24. Lateral Bracing (EA)	350	347	0	3	0	1.14
c25. Sway Bracing (EA)						
c26. Bearing Devices (EA) d	64	49	13	2	0	1.64
c27. Arch (LF)						
c28. Arch Column/Hanger (EA)						
c29. Arch Spandrel Walls (LF)						
c30. Prot. Coating System (LF) d	51322	40029	2784	720	7789	4.00
c31. Pins/Hangers/Hinges (EA) d	16	16	0	0	0	1.00
c32. Fatigue (LF) d	51322	49998	1289	35	0	1.05
N59. Superstructure Summary					(9-0)	6

SUBSTRUCTURE ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c33. Abutment Walls (LF)	160.5	81	78.5	1	0	1.65
c34. Abutment Caps (LF)	160.5	81	78.5	1	0	1.65
c35. Abut. Columns/Bents (EA)	0					
c36. Pier Walls (LF)	429	371	17	41	0	2.00
c37. Pier Caps (LF)	1033.2	790.7	202	40.5	0	1.71
c38. Pier Columns/Bents (EA)	0					
c39. Backwalls (LF)	160.5	0	54	106.5	0	3.00
c40. Wingwalls (EA)	4	4	0	0	0	1.00
c42. Scour (EA) d	16	16	0	0	0	1.00
c43. Slope Protection (EA) d	2	2	0	0	0	1.00
N60. Substructure Summary					(9-0)	6

CULVERT ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c44. General (LF)						
c45. Alignment (LF) d						
c46. Shape (LF) d						
c47. Seams (LF) d						
c48. Headwall/Endwall (LF)						
c49. Scour (LF) d						
c50. Abutments (LF)						
N62. Culvert Summary					(9-0)	N

CHANNEL ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c51. Alignment (LF) d	200.00	200	0	0	0	1.00
c52. Protection (LF) d	200.0	200	0	0	0	1.00
c53. Hydraulic Opening (EA) d	16	16	0	0	0	1.00
c54. Navigation Lights (EA) d						
N61. Channel Summary					(9-0)	7

SIGN/UTILITY ITEMS

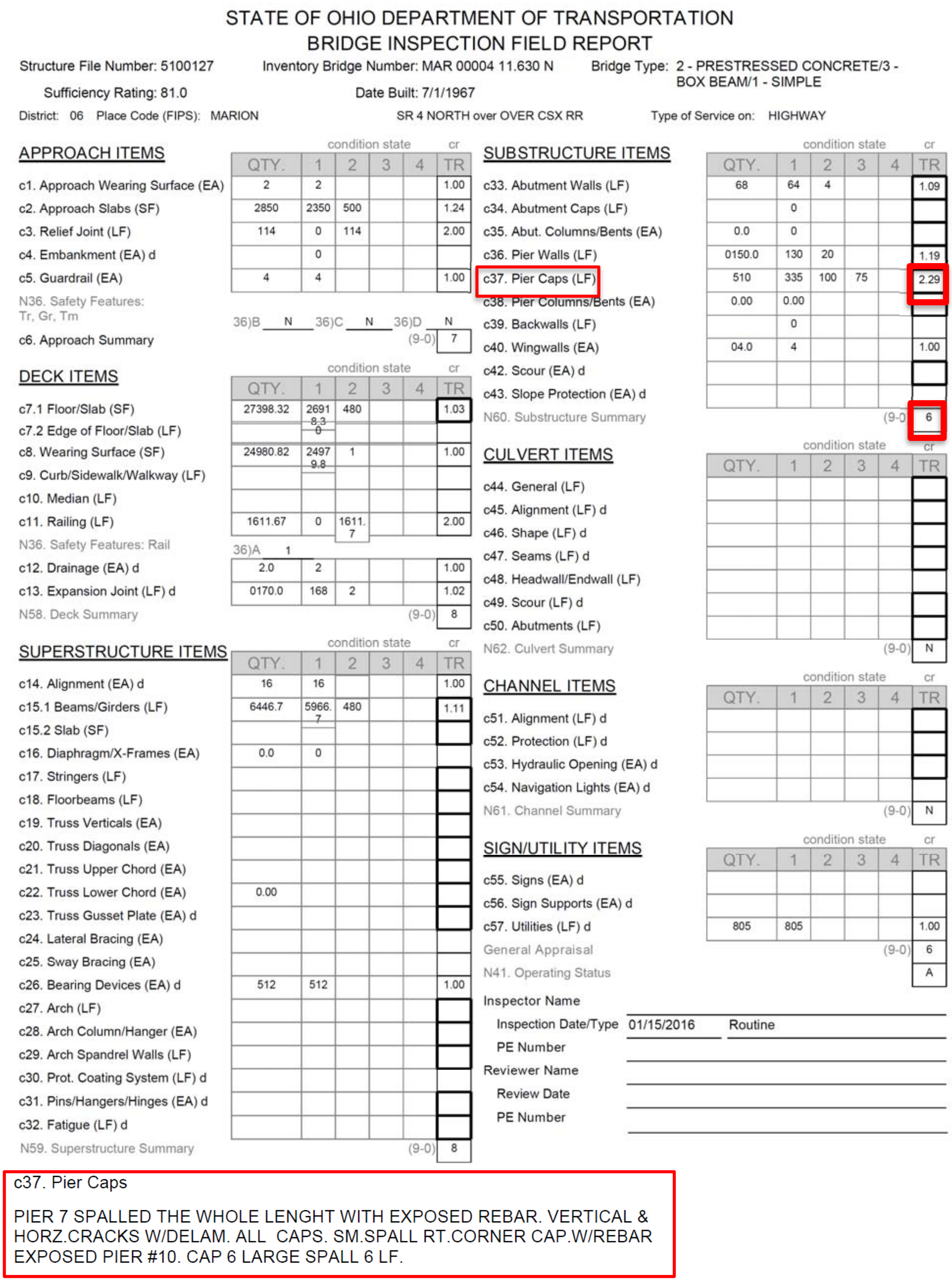
	QTY.	1	2	3	4	TR
		condition state				cr
c55. Signs (EA) d	5	5	0	0	0	1.00
c56. Sign Supports (EA) d	3	1	2	0	0	1.75
c57. Utilities (LF) d	8296	8294	0	2	0	1.00
General Appraisal					(9-0)	6
N41. Operating Status						A

Inspector Name
Inspection Date/Type 09/02/2015 In-Depth and Fracture Critical
PE Number
Reviewer Name
Review Date
PE Number

c7.1 Floor/Slab

Cracks with efflorescence throughout. Spalls, scaling and exposed reinforcement on 9.2% of deck underside. Sub-decking covers West Canal Road, Towpath Trail and Canal Road in spans 8 and 9.

Figure 2-3- Inspection Report of the I-480 E.B. Over Cuyahoga River-Ohio Canal Bridge



STATE OF OHIO DEPARTMENT OF TRANSPORTATION
BRIDGE INSPECTION FIELD REPORT

Structure File Number: 5100127
Inventory Bridge Number: MAR 00004 11.630 N
Bridge Type: 2 - PRESTRESSED CONCRETE/3 - BOX BEAM/1 - SIMPLE
Sufficiency Rating: 81.0
Date Built: 7/1/1967
District: 06 Place Code (FIPS): MARION
SR 4 NORTH over OVER CSX RR
Type of Service on: HIGHWAY

APPROACH ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c1. Approach Wearing Surface (EA)	2	2				1.00
c2. Approach Slabs (SF)	2850	2350	500			1.24
c3. Relief Joint (LF)	114	0	114			2.00
c4. Embankment (EA) d		0				
c5. Guardrail (EA)	4	4				1.00
N36. Safety Features: Tr, Gr, Tm	36)B N	36)C N	36)D N			
c6. Approach Summary					(9-0)	7

DECK ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c7.1 Floor/Slab (SF)	27398.32	2691 8.3 0	480			1.03
c7.2 Edge of Floor/Slab (LF)						
c8. Wearing Surface (SF)	24980.82	2497 9.8	1			1.00
c9. Curb/Sidewalk/Walkway (LF)						
c10. Median (LF)						
c11. Railing (LF)	1611.67	0	1611. 7			2.00
N36. Safety Features: Rail	36)A 1					
c12. Drainage (EA) d	2.0	2				1.00
c13. Expansion Joint (LF) d	0170.0	168	2			1.02
N58. Deck Summary					(9-0)	8

SUPERSTRUCTURE ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c14. Alignment (EA) d	16	16				1.00
c15.1 Beams/Girders (LF)	6446.7	5966. 7	480			1.11
c15.2 Slab (SF)						
c16. Diaphragm/X-Frames (EA)	0.0	0				
c17. Stringers (LF)						
c18. Floorbeams (LF)						
c19. Truss Verticals (EA)						
c20. Truss Diagonals (EA)						
c21. Truss Upper Chord (EA)						
c22. Truss Lower Chord (EA)	0.00					
c23. Truss Gusset Plate (EA) d						
c24. Lateral Bracing (EA)						
c25. Sway Bracing (EA)						
c26. Bearing Devices (EA) d	512	512				1.00
c27. Arch (LF)						
c28. Arch Column/Hanger (EA)						
c29. Arch Spandrel Walls (LF)						
c30. Prot. Coating System (LF) d						
c31. Pins/Hangers/Hinges (EA) d						
c32. Fatigue (LF) d						
N59. Superstructure Summary					(9-0)	8

SUBSTRUCTURE ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c33. Abutment Walls (LF)	68	64	4			1.09
c34. Abutment Caps (LF)		0				
c35. Abut. Columns/Bents (EA)	0.0	0				
c36. Pier Walls (LF)	0150.0	130	20			1.19
c37. Pier Caps (LF)	510	335	100	75		2.29
c38. Pier Columns/Bents (EA)	0.00	0.00				
c39. Backwalls (LF)		0				
c40. Wingwalls (EA)	04.0	4				1.00
c42. Scour (EA) d						
c43. Slope Protection (EA) d						
N60. Substructure Summary					(9-0)	6

CULVERT ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c44. General (LF)						
c45. Alignment (LF) d						
c46. Shape (LF) d						
c47. Seams (LF) d						
c48. Headwall/Endwall (LF)						
c49. Scour (LF) d						
c50. Abutments (LF)						
N62. Culvert Summary					(9-0)	N

CHANNEL ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c51. Alignment (LF) d						
c52. Protection (LF) d						
c53. Hydraulic Opening (EA) d						
c54. Navigation Lights (EA) d						
N61. Channel Summary					(9-0)	N

SIGN/UTILITY ITEMS

	QTY.	1	2	3	4	TR
		condition state				cr
c55. Signs (EA) d						
c56. Sign Supports (EA) d						
c57. Utilities (LF) d	805	805				1.00
General Appraisal					(9-0)	6
N41. Operating Status						A

Inspector Name
Inspection Date/Type 01/15/2016 Routine
PE Number
Reviewer Name
Review Date
PE Number

c37. Pier Caps

PIER 7 SPALLED THE WHOLE LENGHT WITH EXPOSED REBAR. VERTICAL & HORZ.CRACKS W/DELAM. ALL CAPS. SM.SPALL RT.CORNER CAP.W/REBAR EXPOSED PIER #10. CAP 6 LARGE SPALL 6 LF.

Figure 2-4- Inspection Report of the SR 4 North Over CSX RR Bridge

Table 2-4- Element-, component-, and bridge-level OBCI for the I-480 E.B. Over Cuyahoga River-Ohio Canal bridge

OBCI	$OBCI_{min}$	$OBCI_{current}$	$OBCI_{current(risk-based)}$
Bridge-level			
I-480 E.B. Over Cuyahoga River-Ohio Canal bridge	0.958	0.903	0.776
Component-level			
Approach	0.752	0.537	0.537
Deck	0.996	0.846	0.568
Superstructure	0.843	0.825	0.654
Substructure	0.961	0.891	0.357
Channel	1.000	1.000	1.000
Sign	1.000	0.988	0.988
Element-level			
Approach Wearing Surface	0.598	0.248	0.248
Approach Slab	1.000	0.910	0.910
Embankment	1.000	1.000	1.000
Guardrail	1.000	1.000	1.000
Floor/Slab	1.000	0.768	0.411
Edge of Floor/Slab	1.000	0.900	0.900
Wearing Surface	1.000	0.998	0.998
Railing	1.000	0.718	0.718
Drainage	0.881	0.470	0.470
Expansion Joint	0.722	0.722	0.722
Beams/Girders	1.000	0.941	0.501
Stringers	1.000	0.992	0.992
Floorbeams	1.000	0.989	0.989
Lateral Bracing	1.000	0.991	0.991
Bearing Devices	1.000	0.837	0.837
Prot. Coating System	0.479	0.419	0.419
Pins/Hangers/Hinges	1.000	1.000	0.999
Abutment Walls	1.000	0.724	0.723
Abutment Caps	1.000	0.711	0.710
Pier Walls	0.914	0.872	0.093
Pier Caps	0.968	0.909	0.466
Backwalls	0.643	0.481	0.481
Wingwalls	1.000	1.000	1.000
Scour	1.000	1.000	1.000
Slope Protection	1.000	1.000	1.000
Alignment	1.000	1.000	0.998
Protection	1.000	1.000	0.999
Hydraulic Opening	1.000	1.000	1.000
Signs	1.000	1.000	1.000
Sign Supports	1.000	0.080	0.080
Utilities	1.000	0.990	0.990

Table 2-5- Element-, component-, and bridge-level OBCI for the SR 4 North Over CSX RR Bridge

OBCI	$OBCI_{min}$	$OBCI_{current}$	$OBCI_{current(risk-based)}$
Bridge-level			
SR 4 North Over CSX RR Bridge	0.996	0.934	0.876
Component-level			
Approach	1.000	0.926	0.926
Deck	1.000	0.932	0.932
Superstructure	1.000	0.979	0.979
Substructure	0.912	0.793	0.339
Sign	1.000	1.000	1.000
Element-level			
Approach Wearing Surface	1.000	1.000	1.000
Approach Slab	1.000	0.868	0.868
Embankment	1.000	1.000	1.000
Guardrail	1.000	1.000	1.000
Floor/Slab	1.000	0.980	0.980
Wearing Surface	1.000	0.992	0.992
Railing	1.000	0.367	0.367
Drainage	1.000	1.000	1.000
Expansion Joint	1.000	1.000	1.000
Beams/Girders	1.000	0.948	0.948
Bearing Device	1.000	1.000	1.000
Abutment Walls	1.000	0.602	0.602
Pier Walls	1.000	0.777	0.776
Pier Caps	0.862	0.728	0.235
Wingwalls	1.000	1.000	1.000
Utilities	1.000	1.000	1.000

Table 2-6- Comparison of the $OBCI_{current}$ and $OBCI_{current(risk-based)}$ for the Floor/Slab Element of the I-480 E.B. Over Cuyahoga River-Ohio Canal Bridge and the Pier Caps Element of the SR 4 North CSX RR Bridge

	$OBCI_{current}$	$OBCI_{current(risk-based)}$
I-480 E.B. Over Cuyahoga River-Ohio Canal Bridge		
Floor/Slab Element	0.768	0.411
Deck Component	0.846	0.568
Bridge	0.903	0.776
SR 4 North CSX RR Bridge		
Pier Caps Element	0.728	0.235
Substructure Component	0.793	0.339
Bridge	0.934	0.876

3. Cost and OBCI values for the entire NHS bridges in district 10 of Ohio

For automatic calculation of costs and OBCI values for any selection of bridges, a module-based computer program is developed in this project. This program is explained in detail in Appendix D. Employing this computer program on inspection reports of 2017, cost and OBCI values are calculated for the entire National Highway System (NHS) bridges in district 10 of Ohio. Notably, at this point, ODOT has provided element-level inspection evaluations for 4754 NHS bridges in Ohio. The total number of NHS bridges in district 10 is also derived as 228, and the total deck area of these bridges is calculated as 2,126,158 ft^2.

3.1 Agency and user costs

For the two targets of having all bridges in 1) a condition better than their minimum safe and serviceable, and 2) like-new states, the incurred user and agency costs are separately calculated and presented in Table 3-1. In addition, the unit cost per deck area (\$/ft^2) to reach these targets are provided, as well.

Table 3-1- Total required agency and user costs for repairs on bridges in district 10

	Target			
	Minimum Safe & Serviceable State		**Like-New State**	
Network-level Costs	**Total Cost ($)**	**Unit Cost per Deck Area (\$/ft^2)**	**Total Cost ($)**	**Unit Cost per Deck Area (\$/ft^2)**
Agency Costs	98.1M	46.1	172.7M	81.2
User Costs	95.0M	44.7	218.5M	102.8
Sum	193.1M	90.82	391.2M	184.0

As can be seen, the required cost to have all the bridges in the like-new state is almost two times the cost to have all bridges in the minimum safe and serviceable state. Additionally, the order of direct costs on the agency is similar to the cost indirectly imposed on users.

In a more refined study, authors calculated the distribution of agency and user costs of bridges in district 10 that are required to achieve minimum safe and serviceable and like-new states. These results are plotted in Figure 3-1-a and Figure 3-1-b, respectively. For instance, results show that around 33% of bridges require an agency cost between \$0-\$600K to be improved to minimum safe and serviceable state, while to reach to the like-new state, around 60% of bridges incur this range of cost on the agency. Furthermore, around 45% of bridges are in their minimum safe and serviceable state, whereas only 5% of bridges are in the decent like-new state. Noticeably, the maximum range of incurred agency cost to achieve minimum safe and serviceable, and like-new states is \$5.5M-\$6.1M. These values increase up to two times for user-induced costs; showing the significance of incorporating user costs in assigning optimal repair actions.

In Figure 3-2, the distribution of costs with respect to components of bridges in district 10 is shown. As can be seen, deck, followed by superstructure, are the most costly components. Furthermore, to achieve the minimum safe and serviceable state, district 10 is recommended to allocate two times more budget on decks than superstructures.

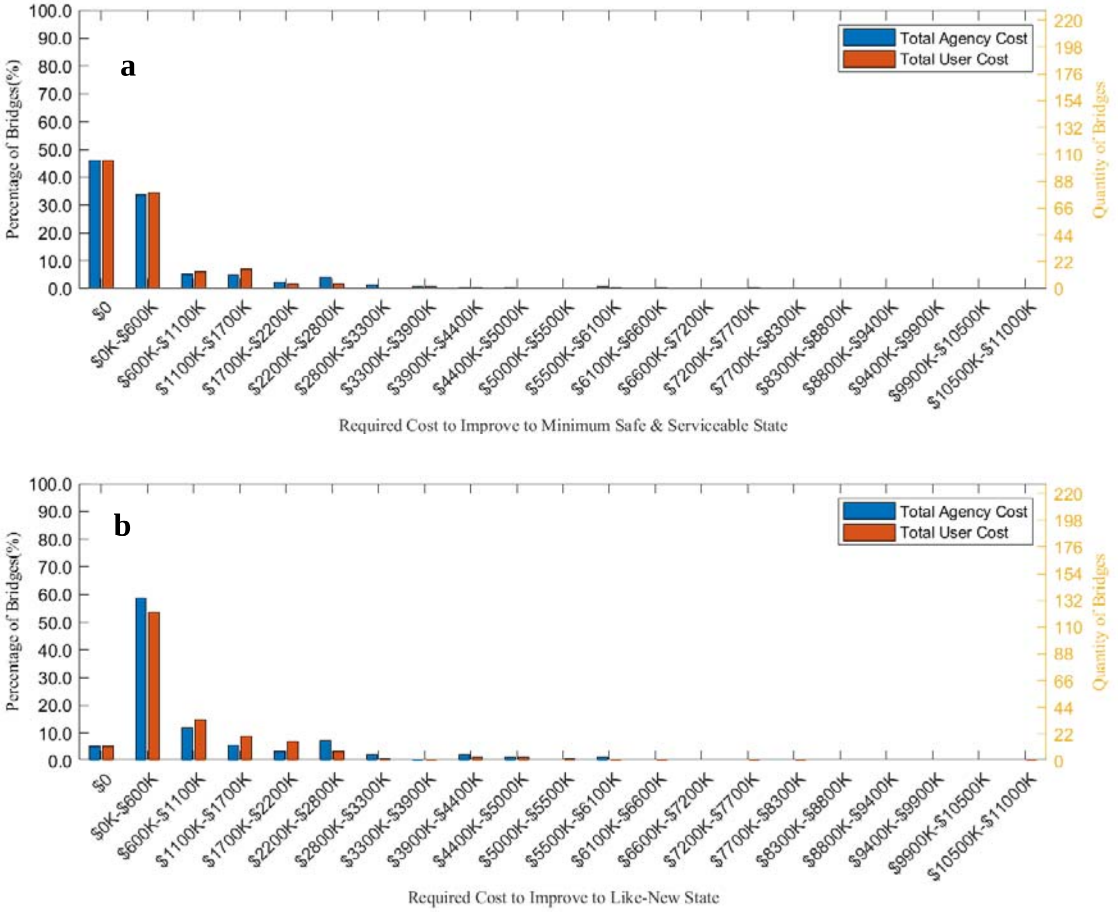


Figure 3-1- Distribution of agency and user costs required for repairs on bridges in District 10 to reach a) minimum safe and serviceable, and b) like-new states

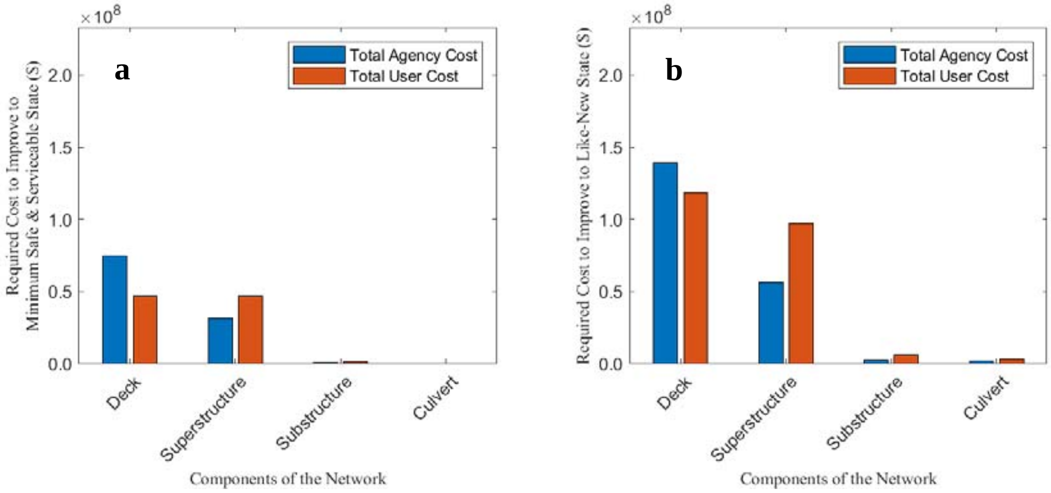


Figure 3-2- Agency and user costs required for repairs of bridge components in district 10 to reach a) minimum safe and serviceable, and b) like-new states

3.2 OBCI values

Based on the developed computer program, $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ for NHS bridges in district 10 are also calculated. At network-level, these values are presented in Table 3-2.

Table 3-2- Network-level $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ for the entire NHS bridges in district 10

	$\boldsymbol{OBCI_{min}}$	$\boldsymbol{OBCI_{current}}$	$\boldsymbol{OBCI_{current(risk-based)}}$
District 10	**0.835**	**0.666**	**0.649**

Having generated these results for the entire 12 districts in ODOT, performance of NHS bridges among ODOT's districts can be compared. Furthermore, according to the formulation of OBCI and the results of $OBCI_{min}$ and $OBCI_{current}$ presented in Table 3-2, 17% and 34% of the total replacement cost of bridges in district 10 is required to bring all bridges to their minimum safe and serviceable, and like-new states, respectively. These costs that are presented in Table 3-1 are the sum of user and agency costs that are incurred as a result of MR&R work plans on bridge elements.

In more details, $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ are calculated for the 228 NHS bridges in district 10, at element-, and component-level, respectively. These results are shown in Figures 3-3, and 3-5, respectively. According to Figure 3-3, it is realized that, in terms of severity and extent of defects, 45% of bridges in this district are in the safe and serviceable condition. That is, $OBCI_{min}$ of 45% of bridges is 1.0. However, only 5% of bridges in this district are in their like-new state; i.e. they have $OBCI_{current}$ of 1.0.

Another finding is that the cost of repairing two bridges, i.e. bridges with SFN "3700453" and "8403570", to above their minimum safe and serviceable threshold is as high as 85-90% of the cost of replacing them. Notably, this cost is the sum of user and agency costs, considering both ODOT and the community, to which these bridges serve. If the target is to improve their like-new state, this cost becomes larger than 90%. Thus, ODOT is recommended to replace these two bridges.

As a general trend, the percentage of bridges with low OBCI values is less than the percentage of bridges with high OBCI values. In total, $OBCI_{min}$ of 78% of bridges is above 0.9, showing that a large portion of bridges in this district are close to the minimum safe and serviceable state. Results also indicate that $OBCI_{current}$ of about 55% of bridges within this district is above 0.8, which implies that almost half of bridges require MR&R funds to improve to their like-new state. Moreover, the distribution of bridges in various ranges of $OBCI_{current(risk-based)}$ is generally similar to that of $OBCI_{current}$. Looking at the formulation of $OBCI_{current}$ and $OBCI_{current(risk-based)}$, this implies that not many bridges have serious safety concerns.

Looking at General Appraisal (GA) values of bridges in district 10 presented in Figure 3-4, about 93% of these bridges are rated as "Satisfactory", "Good", "very Good", and "Excellent", indicating that these bridges have minor or no deterioration. This result may be comparable with the 89% of bridges having $OBCI_{min}$ greater than 0.5. On the other hand, the GA of two bridges with SFN "0505927" and "2700301" are rated as "Poor" which meets the definition of "structurally deficient" bridges according to American Society of Civil Engineers (24). On this basis, these bridges are candidates for federal replacement funds (2,25). Looking further into the first bridge, only one out of the three components of this bridge, i.e. deck component, is rated "Poor", while the others are rated "Very Good". This may result in misleading evaluations about the required repair cost of these bridges, as GA of these bridges is "Poor". This issue is properly reflected in OBCI, as the $OBCI_{min}$ of 0.43 for this bridge implies that 57% of the bridge replacement cost suffices for having the bridge at the acceptable minimum safe and serviceable state. This observation promotes cost-effective repairs, rather than the costly replacement action. On the other hand, $OBCI_{current}$ of this bridge is calculated as 0.22, indicating that a minimum of around 80% of the bridge replacement cost is required to improve the bridge to its like-new state. This may result in the decision of replacement if the target is to reach the like-new state for this bridge.

As can be seen, GA neither reflect details of element conditions and serviceability features of bridges, nor delivers any information about the required cost of repair, which is essential for budget allocation and management; on the other hand, these are the capabilities offered by OBCI metrics. Furthermore, OBCI is showing more sensitivity than GA appraisals, as OBCI is a continuous index varying from 0 to 1 (which is categorized in 12 seeds in Figures 3-3 and 3-5), whereas GA is a discrete rating varying from 4 to 9. This makes OBCI a more effective index to prioritize bridges that need different types of maintenance considering safety, practicality and total incurred costs.

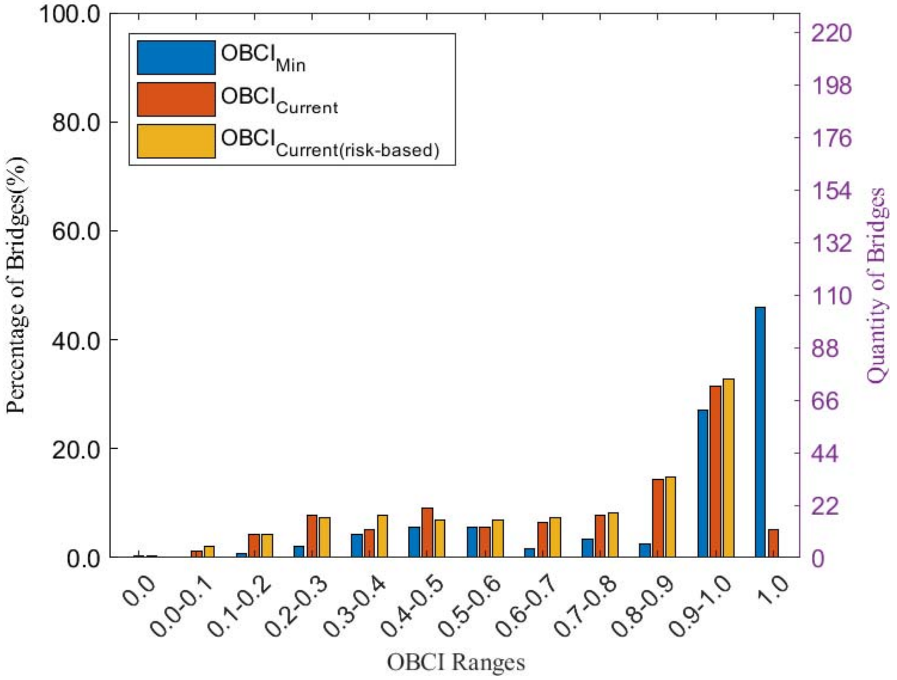


Figure 3-3- Percentage of NHS bridges of district 10 in various ranges of $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$

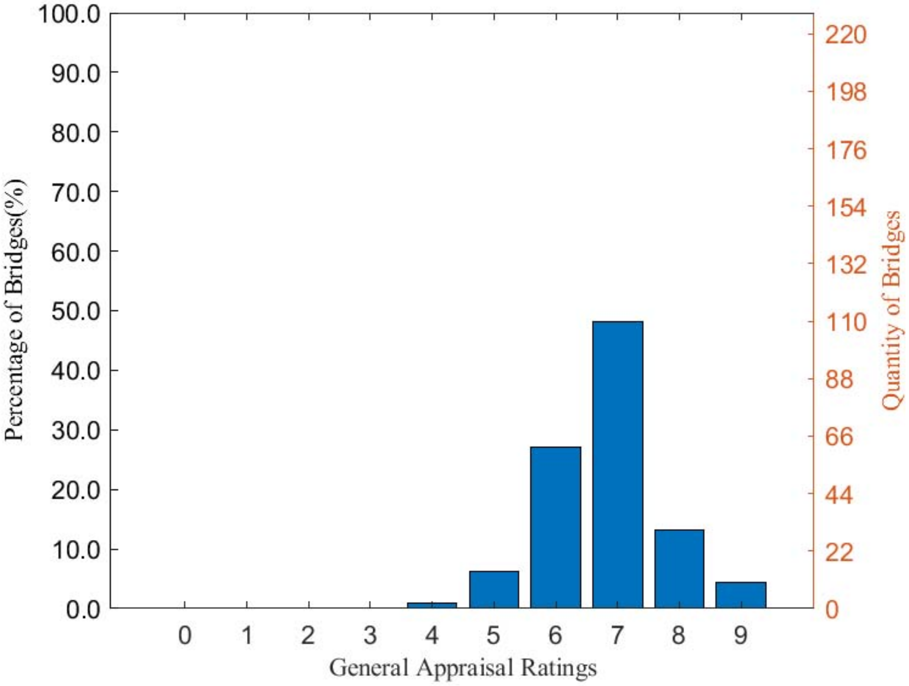


Figure 3-4- Percentage of NHS bridges of district 10 in general appraisal ratings of 0 to 9

Another study is also conducted for evaluating the performance of individual bridge components. To this end, percentage of deck, superstructure, substructure, and culvert components of district 10 in various ranges of $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ are derived and plotted in Figure 3-5. As shown, substructures and culverts, with around 80% having $OBCI_{min}$ of one, are the most structurally safe and serviceable components. Additionally, based on the results of $OBCI_{current(risk-based)}$, which includes safety risks in addition to other costs, culverts with around 30%, and substructures with around 80% having $OBCI_{current(risk-based)} \geq 0.9$ are found to be the most critical, and the safest among components, respectively. This can be also confirmed by the GA appraisals shown for deck, superstructure, substructure, and culvert components in Figure 3-6. The percentage of the culvert component with GA appraisal of 6 and below is almost three times more than that for other components. Similar to the trend observed for the bridge-level OBCIs, a large quantity of components have high OBCI values.

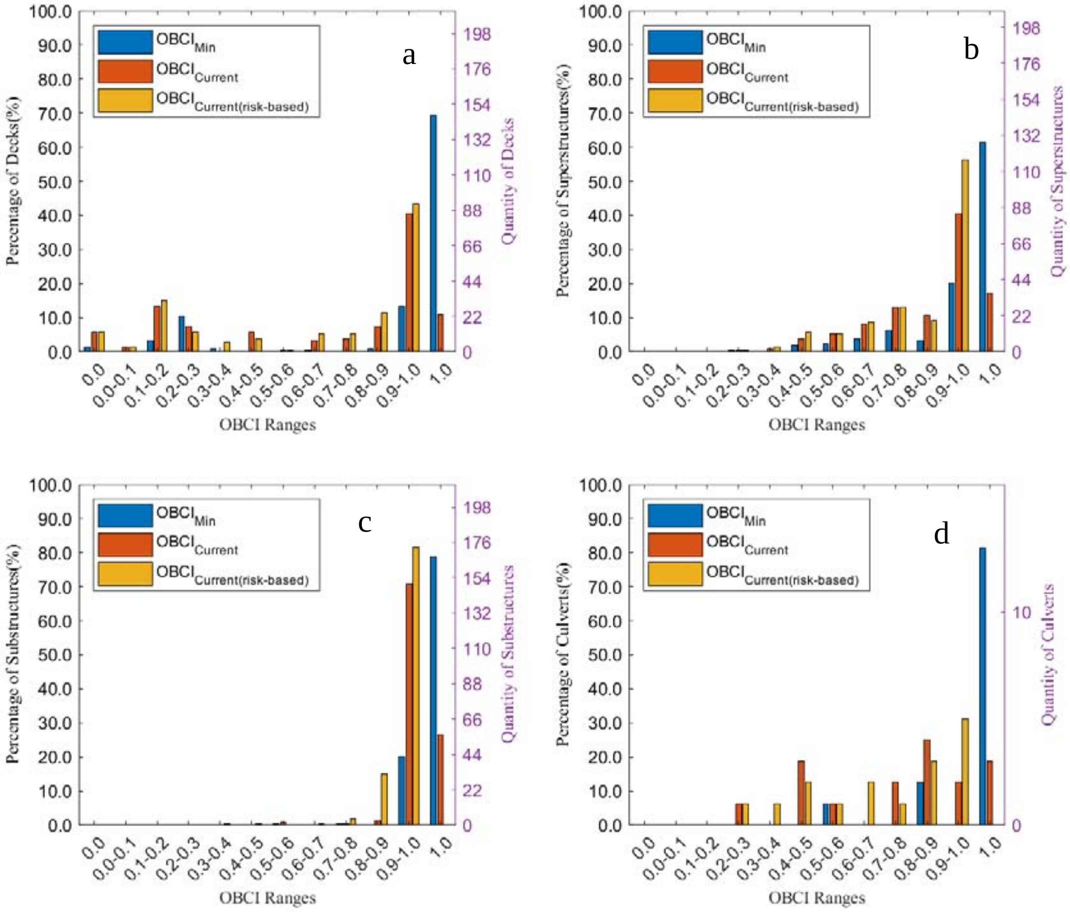


Figure 3-5- Percentage of a) deck b) superstructure c) substructure and d) culvert components of district 10 in various ranges of $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$

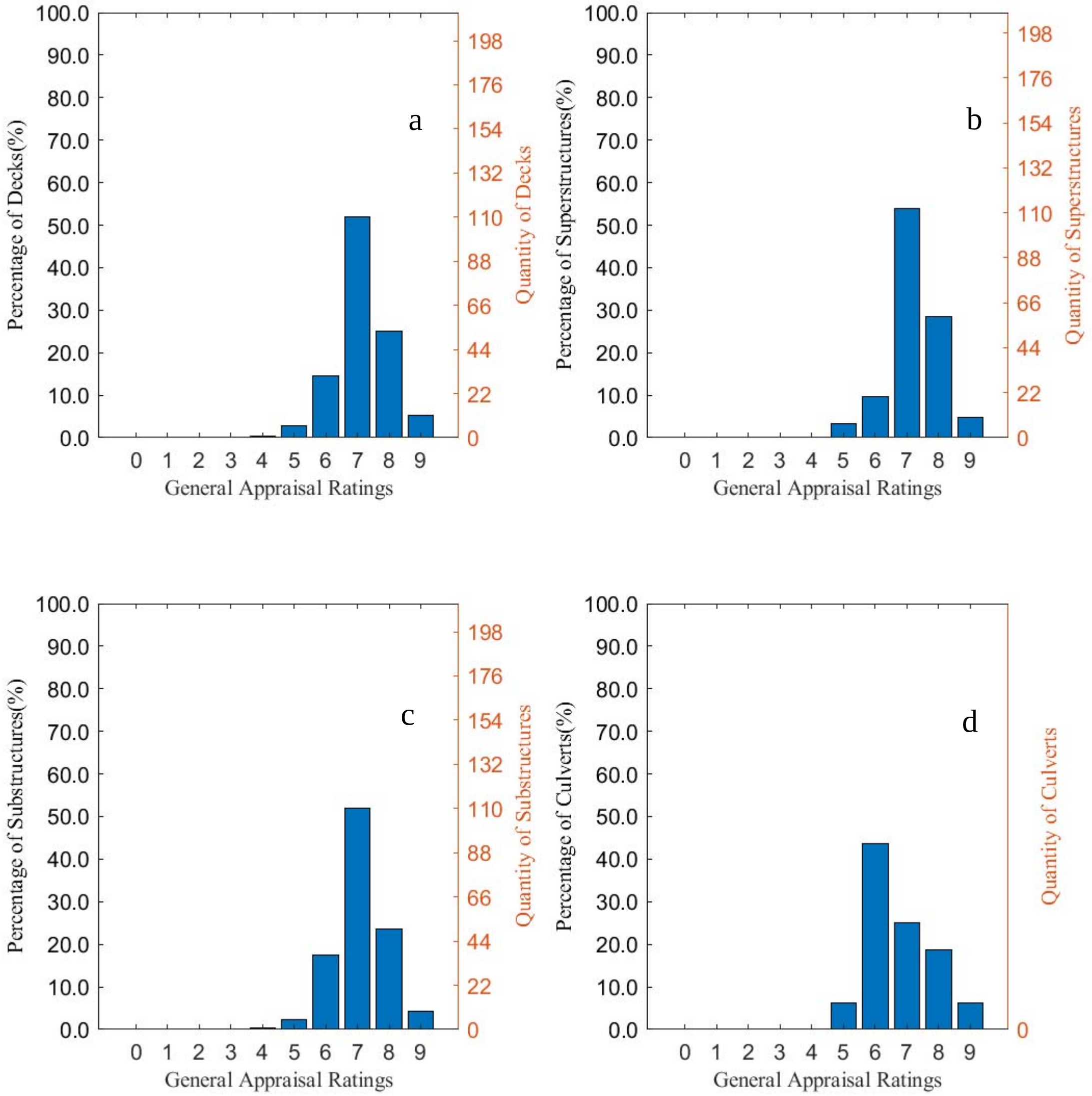


Figure 3-6- Percentage of a) deck b) superstructure c) substructure and d) culvert components of district 10 with general appraisal ratings of 0 to 9

4. An optimal budget allocation algorithm with constraints on budget

In another phase of the project, an optimal budget allocation algorithm is proposed that suggests the optimal MR&R work plan for NHS bridges of ODOT's districts.

The algorithm identifies optimal MR&R actions for elements of NHS bridges in districts such that:

- The cost of implementing those actions does not exceed the available budget of the district,
- The safety and serviceability performance of NHS bridges in the district is maximized.

In the rest of this section, first, an overview of the proposed budget allocation algorithm is provided. Then, the results of a runtime study is presented. Based on this study ODOT engineers can estimate the runtime required to conduct the developed optimization program on a bridge portfolio, given the number of bridges in that selection. Then, an enhancement to the algorithm is presented, which enables ODOT engineers to acquire more than one set of optimal work plans for their selected bridge portfolios. In the next section, considering one set of optimal work plans, the optimal MR&R actions for the entire NHS bridges in district 3 of Ohio is identified and discussed. This section is followed by a study on the validation and verification of the results from the proposed optimal budget allocation algorithm.

4.1 Overview of the developed optimal budget allocation algorithm

The objective is to maximize the performance of NHS bridges in district 3 after performing MR&R actions. The considered performance measure is the network-level $OBCI_{current(risk-based)}$, which objectively incorporates safety and serviceability features of bridges. According to Equation (2-4), network-level $OBCI_{current(risk-based)}$ can be formulated as:

$$OBCI_{current(risk-based)_N} = 1 - \frac{\sum_{B=1}^{M_N}\left(1-P_B^f\right)\times\left(AC_B^{ln}+UC_B^{ln}\right)+P_B^f\times\left(AC_B^{rep}+UC_B^{rep}\right)}{\sum_{B=1}^{M_N}\left(AC_B^{Rep}+UC_B^{Rep}\right)} \tag{4-1}$$

where $OBCI_{current(risk-based)_N}^{after\ MR\&R\ actions}$ is the network-level $OBCI_{current(risk-based)}$ of the selected bridges, P_B^f is the probability of improper functionality of bridge B, AC_B^{ln} and UC_B^{ln} are the costs incurred on the agency and users to improve bridge B to its like-new state, AC_B^{rep} and UC_B^{rep} are the costs incurred on the agency and users to replace bridge B, and M_N is the total number of bridges in the network.

Now, the objective is to find the MR&R work plan such that the performance of the network is maximized. Based on Equation (4-1), the mathematical representation of the objective in the optimal budget allocation problem becomes:

$$\begin{aligned} Objective\!: \max\left(OBCI_{current(risk-based)_N}^{after\ MR\&R\ actions}\right) \\ = \max_j\left(\left\{1-\frac{\sum_{B=1}^{M_N}\sum_{j=1}^{A_B}\left(1-P_{B,j}^f\right)\times\left(AC_{B,j}^{ln}+UC_{B,j}^{ln}\right)+P_{B,j}^f\times\left(AC_{B,j}^{rep}+UC_{B,j}^{rep}\right)}{\sum_{B=1}^{M_N}\left(AC_{B,j}^{Rep}+UC_{B,j}^{Rep}\right)}\right\}\times x_{B,j}\right) \end{aligned} \tag{4-2}$$

where $OBCI_{current(risk-based)_N}^{after\ MR\&R\ actions}$ is the network-level $OBCI_{current(risk-based)}$ of the selected bridges after performing a work plan, $P_{B,j}^f$ is the probability of improper functionality of bridge B after performing work plan j, $AC_{B,j}^{ln}$ and $UC_{B,j}^{ln}$ are the costs incurred on the agency and users to improve bridge B to its like-new state after performing work plan j, $AC_{B,j}^{rep}$ and $UC_{B,j}^{rep}$ are the costs incurred on the agency and users to replace bridge B after performing work plan j, $x_{B,j}$ is a variable taking the value of 0 or 1, indicating consideration of or disregard of a set of MR&R actions on elements of bridge B in work plan j, and A_B is the total number of action combinations for bridge B.

Evidently, selection of any work plan j does not affect the term in the denominator of Equation (4-2), i.e. $\sum_{B=1}^{M_N}\left(AC_{B,j}^{Rep}+UC_{B,j}^{Rep}\right)$. Additionally, maximizing 1 minus a term is equal to minimizing that term. Therefore, the objective can be expressed by:

$$Objective\!: \min_j\left(\left\{\sum_{B=1}^{M_N}\sum_{j=1}^{A_B}\left(1-P_{B,j}^f\right)\times\left(AC_{B,j}^{ln}+UC_{B,j}^{ln}\right)+P_{B,j}^f\times\left(AC_{B,j}^{rep}+UC_{B,j}^{rep}\right)\right\}\times x_{B,j}\right) \tag{4-3}$$

Equation (4-3) shows that the objective of the problem is also to minimize annual safety risks of bridges and the serviceability interruptions on users due to repair actions that are required to improve the bridges to their like-new state.

Considering a maximum value in the agency's budget for MR&R actions, and the entire possibilities for practical MR&R actions for each bridge in the network, the optimal budget allocation algorithm can be articulated as follows:

$$Objective: \min_{j}\left(\left\{\sum_{B=1}^{M_N}\sum_{j=1}^{A_B}\left(1-P_{B,j}^{f}\right)\times\left(AC_{B,j}^{ln}+UC_{B,j}^{ln}\right)+P_{B,j}^{f}\times\left(AC_{B,j}^{rep}+UC_{B,j}^{rep}\right)\right\}\times x_{B,j}\right)$$

$$Subject\ to: \begin{cases} \displaystyle\sum_{B=1}^{M_N}\sum_{j=1}^{A_B} AC_{j,B}\times x_{j,B}\leq Budget \\ x_{j,B}\in\{0,1\} \\ \displaystyle\sum_{j=1}^{A_B} x_{j,B}=1\ \ for\ each\ B=1\ldots\ M_N \end{cases} \tag{4-4}$$

where $Budget$ is the maximum available budget for the entire network.

Before solving Equation (4-4), for the identification of action possibilities for a bridges, some safety-related and practical constraints are considered, including:

1) If the maximum available budget is less than or equal to the required budget to improve all bridge elements in the network to their minimum safe and serviceable state, which was identified in Section 2.2.1, the available budget is allocated for critical repairs, rather than maintenance actions. Critical repairs are repair actions that improve the condition of elements in such a way that:

   - The summary rating of the component containing that element is greater than or equal to 6 (i.e. “satisfactory”), and
   - For primary bridge elements, such as girders, less than 2% is in condition-state 3, while no quantity is in condition-state 4, and
   - For non-primary bridge elements, such as railings, less than 10% is in condition-state 3 and 4.

   These conditions are referred to as “minimum safe and serviceable state with no safety concern” in the rest of this report.

2) If the maximum available budget is more than the required budget to improve all bridge elements in the network to their minimum safe and serviceable state, the available budget is allocated in such a way that all elements with a condition worse than the “minimum safe and serviceable state with no safety concern” should receive at least critical repairs.

3) For practical considerations, all elements within a component receive identical *type* of action: That is, either of the following:

   - No action for all elements,
   - Those that have a condition worse than their “minimum safe and serviceable state with no safety concern” receive critical repairs, as follows:
     - All portions of the element that are in condition-state 3 and 4 should be repaired to be improved to at least condition-state 2.
     - If no portions of the element are in condition-state 3 and 4, those quantities of the element in condition-state 2 should receive maintenance/preservation actions.
   - All elements receive critical repairs together with maintenance actions,
   - The component will be replaced.

4) If sum of the costs of an MR&R action on a component is larger than the sum of the replacement cost of that component, the latter is considered.

5) If sum of the costs of MR&R actions on components of a bridge is more than the sum of the costs of replacing the bridge, the latter is considered.

As an example, let's assume bridge D with three components:

- Deck and superstructure with some elements that are in need of minimum critical repairs and
- Substructure that includes elements, all with condition-states better than their "minimum safe and serviceable state with no safety concern", but below like-new.

Considering that the available budget for this bridge is more than the required budget to improve all elements to their minimum safe and serviceable state, the total number of action combinations becomes eight, as shown in Table 4-1.

Table 4-1- Action combinations for an arbitrary bridge with three components

Bridge	Components: Action possibilities the component	MR&R Work Plan Combinations
D	Deck: min, like-new Superstructure: min, like-new Substructure: do nothing, like-new	$C_{Deck}^{min}, C_{Sup}^{min}, C_{Sub}^{do\ nothing}$
		$C_{Deck}^{min}, C_{Sup}^{min}, C_{Sub}^{like-new}$
		$C_{Deck}^{min}, C_{Sup}^{like-new}, C_{Sub}^{do\ nothing}$
		$C_{Deck}^{min}, C_{Sup}^{like-new}, C_{Sub}^{like-new}$
		$C_{Deck}^{like-new}, C_{Sup}^{min}, C_{Sub}^{do\ nothing}$
		$C_{Deck}^{like-new}, C_{Sup}^{min}, C_{Sub}^{like-new}$
		$C_{Deck}^{like-new}, C_{Sup}^{like-new}, C_{Sub}^{do\ nothing}$
		$C_{Deck}^{like-new}, C_{Sup}^{like-new}, C_{Sub}^{like-new}$

Note: Action possibility "min"=critical repairs, Action possibility "like-new"=Actions that improve the condition-state of all elements in the component to their like-new state

One way to solve Equation (4-4) is through one-by-one evaluation of all possible combinations of MR&R actions from all the bridges in the network. However, this approach becomes computationally prohibitive if the number of bridges are even slightly large. For instance, if a portfolio of ten bridges is considered, where each bridge has eight possible action combinations like the arbitrary bridge D in the previous example, the total number of action possibilities for the entire portfolio becomes $8^{10} \cong 10^{9}$. One efficient substitute for this approach is the application of the theory of mixed-integer linear programming. Through this algorithm, the optimal work plan is found within a practical time. That is, for the 484 bridges in district 3 of Ohio, the optimization analysis took around 20 hours on a normal personal computer with a core-i7 processor.

Furthermore, in this research project, MATLAB 2018a is used for the application of the efficient theory of mixed-integer linear programming for the optimal budget allocation problem. Information about the details of the mixed-integer linear programming algorithm used by this software can be found in the documentation of MATLAB 2018a at https://www.mathworks.com/help/optim/ug/mixed-integer-linear-programming-algorithms.html#btv2z9y. According to the documentation, "Branch and Bound" is the systematic solution algorithm of the software, which can be studied in more details in (26). This algorithm successively builds subdivisions to find the absolute optimal solution or get very close to the absolute solution approximated with a tolerance value.

It is worthy to note that the developed optimal budget allocation algorithm systematically gives higher importance to work plans that reduce safety risks of bridges, e.g. to bridges with low General Appraisal values. In addition, bridges with high ADT and long detour length, generally gain priority for MR&R

actions over those with lower ADT and shorter detours.

However, as of this time, deterioration models are not included in the optimization framework. Consequently, prioritization does not consider postponing repair actions to a later time in order to, for example, conduct more extensive repairs or replace the bridge. In addition, uncommon costly consequences due to some MR&R actions on bridges with special features are not considered. Some of these bridge include those on railroads, or deep and wide waterways.

4.2 A runtime study for the budget allocation algorithm

In order to examine the practicality of the proposed budget allocation algorithm for large portfolios of Ohio bridges, OSU research team conducted a study to estimate the required runtime for identifying optimal MR&R work plans for a portfolio of bridges as a function of the number of bridges. In this study, 1, 2, 5, 10, 50, 100, 150, and 225 bridges were randomly selected from district 3 and the optimization algorithm were conducted for these bridges. For each of the cases, the required runtime was evaluated for four different stages of analysis that exist in the developed computer program. These stages are:

- Stage 1: OBCI Calculations: Calculating element-, component-, bridge-, and network-level OBCI values and costs.
- Stage 2: Output Generation: Generation of output OBCI and cost tables, as well as graphs and charts to display in the graphical application.
- Stage 3: Identification of Optimal MR&R actions: Calculation of optimal MR&R work plans using the developed budget allocation algorithm for the selected bridges.
- Stage 4: Post-Repair OBCI Calculations: Calculating element-, component-, bridge-, and network-level OBCI and costs after identified repair plans are performed.

The plot of the required runtime for each of the eight cases in all stages are shown in Figure 4-1. As can be seen, the most time-consuming stage is the optimal repair plan identification, which takes almost half of the time of the entire analysis. A prediction model with a very high goodness of fit (R^2) value, i.e. 0.9996, is regressed and plotted in Figure 4-2. According to this function, the required runtime, in hours, for any number of bridges, $PR(M_N)$, using the developed computer code can be estimated based on the following equation:

$$PR(M_N) = 7.989e - 05 \times {M_N}^2 + 0.004813 \times M_N + 0.03404 \qquad (4\text{-}5)$$

where M_N is the total number of bridges considered in the optimal budget allocation analysis. Based on this prediction model, as an example, for optimal budget allocation of all 627 NHS bridges in district 8, which currently has the largest number of NHS bridges in all districts, the required runtime is 34.5 hours.

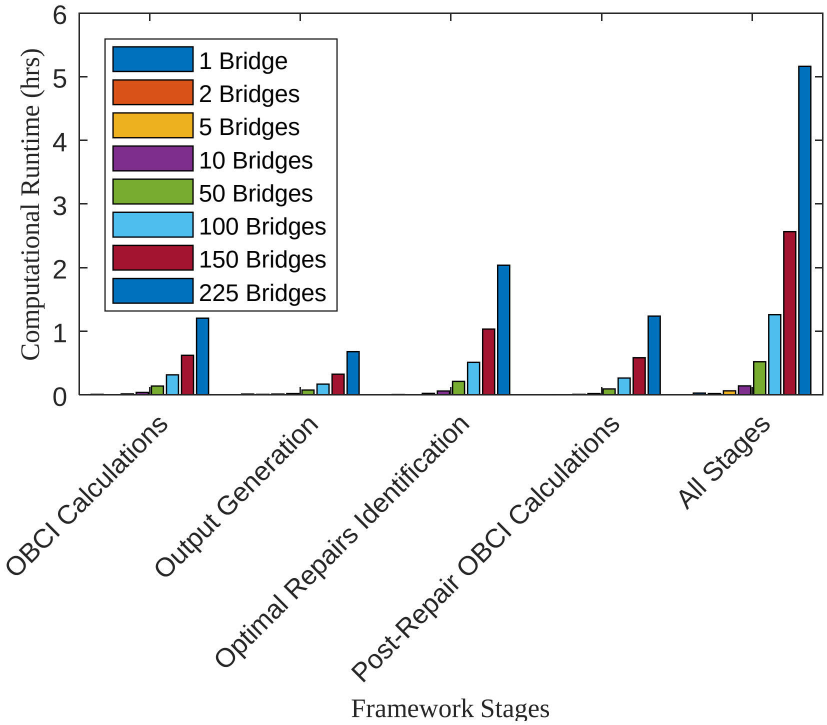


Figure 4-1- Required runtime in various stages of analysis, calculated for six cases of the number of bridges considered for optimal identification of MR&R work plans

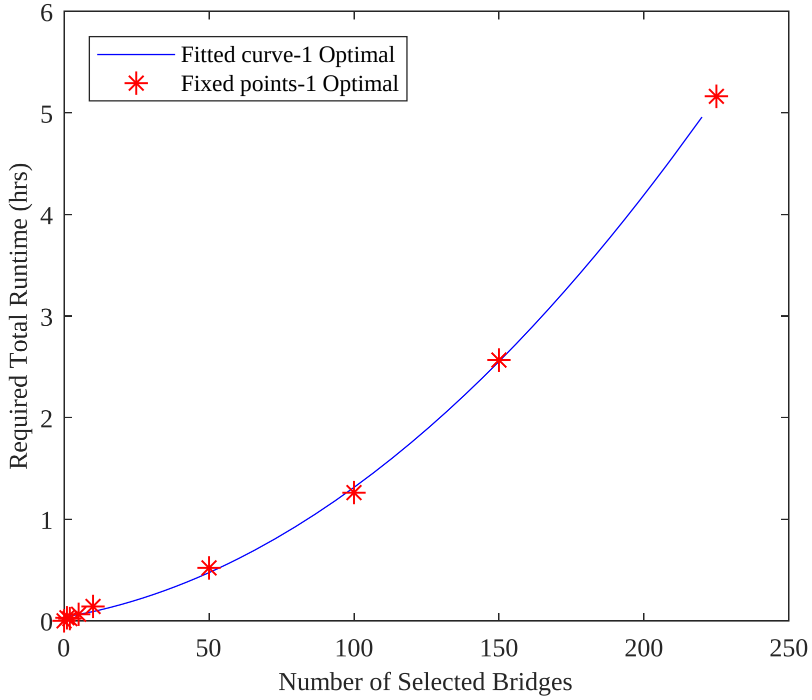


Figure 4-2- Second order polynomial regression model for prediction of the required runtime for optimal identification of MR&R work plans

4.3 A framework for generating multiple optimal solutions for the budget allocation algorithm

Considering that there may be practical issues other than those considered in this framework, ODOT showed interest in being provided multiple optimal and suboptimal solutions for the budget allocation problem. On this basis, ODOT can choose the optimal solution that is the closest match when unpredicted practical issues prohibit some action plans on bridges. For this reason, an enhancement is implemented on the mixed-integer linear programming algorithm presented in Equation (4-4), as follows: An additional constraint is added to the list of constraints in Equation (4-4), and the optimization problem is solved again to develop a new solution. This constraint assures that the objective function, which is minimizing the risk costs incurred on the agency and users to improve the network to the like-new state, is more than this value after performing the most optimal repair plan on the network. This constraint obligates the optimization solver to find the second most optimal solution for the budget allocation problem. This process continues until as many as optimal solutions that the user is asking is calculated by the computer code, or all feasible repair plans, which cost less than the budget limit, are identified by the code. In mathematical terms, for each optimal solution, e.g. *k*th solution, the following mixed-integer programming problem should be solved:

$$Objective\text{: } \min_{j}\left(\left\{\sum_{B=1}^{M_N}\sum_{j=1}^{A_B}\left(1-P_{B,j}^{f}\right)\times\left(AC_{B,j}^{ln}+UC_{B,j}^{ln}\right)+P_{B,j}^{f}\times\left(AC_{B,j}^{rep}+UC_{B,j}^{rep}\right)\right\}\times x_{j,B}^{k}\right)$$

$$Subject\ to\text{: }\begin{cases}\displaystyle\sum_{B=1}^{M_N}\sum_{j=1}^{A_B}\left(1-P_{B,j}^{f}\right)\times\left(AC_{B,j}^{ln}+UC_{B,j}^{ln}\right)+P_{B,j}^{f}\times\left(AC_{B,j}^{rep}+UC_{B,j}^{rep}\right)\times x_{j,B}^{k} > V_{k-1}^{*}\\ \displaystyle\sum_{B=1}^{M_N}\sum_{j=1}^{A_B}AC_{j,B}\times x_{j,B}^{k}\leq Budget\\ x_{j,B}^{k}\in\{0,1\}\\ \displaystyle\sum_{j=1}^{A_B}x_{j,B}^{k}=1\ \ for\ each\ b=1\ldots M_N\end{cases}\tag{4-6}$$

where V_{k-1}^{*} is the risk costs incurred on the agency and users to improve the network to its like-new state followed by performing the *k*-1th optimal repair plan, and $x_{j,B}^{k}$ is a variable taking the value of 0 or 1, indicating consideration of or disregard of work plan *j* for bridge *B* at *k*th optimal solution.

Following the foregoing procedure, the optimization module of the developed computer code is enhanced to include the following steps:

a) Get the desired number of optimal solutions from the user.

b) Calculate the first optimal MR&R plans for bridges in the network, using Equation (4-4)

c) Calculate the optimal objective function associated with this first optimal work plan and store it.

d) Compute new optimal MR&R plans for bridges in the network, using Equation (4-6), where V_{k-1}^{*} in this equation is the objective function calculated from previous step.

e) Calculate the optimal objective function associated with the new optimal plan and store it.

f) If desired number of solutions are identified or all feasible repair plans that cost less than the budget limit are found, stop the algorithm. Otherwise, go to “Step d”.

4.4 Optimal MR&R actions for the entire NHS bridges in district 3 of Ohio

The developed computer code for the optimal allocation of budget is utilized for the assignment of optimal

MR&R work plan for the 484 NHS bridges in district 3, using element-level inspection data collected in 2017. For this purpose, a budget limit of $14,344,280 was considered. According to the feedbacks received from district 3 engineers, the minimum agency cost for any MR&R project on a bridge is considered as $20K. This value is an input for the developed computer program, as well.

Based on the cost calculations of the OBCI framework, the minimum required cost to have all the elements of the 484 bridges in their minimum safe and serviceable state is estimated as $171.42 Million. This budget is called "minimum required budget". The maximum required cost to improve all elements of these bridges to their like-new state is also estimated as $304.0 Million. This budget is called "maximum required budget" in this report. The network-level OBCI before and after implementing the suggested optimal MR&R work plan are shown in Table 4-2.

Table 4-2- Network-level OBCI before and after implementing the suggested optimal MR&R work plan

District 3	$\boldsymbol{OBCI_{min}}$	$\boldsymbol{OBCI_{current}}$	$\boldsymbol{OBCI_{current(risk-based)}}$
Before Performing Optimal MR&R Actions	**0.884**	**0.729**	**0.705**
After Performing Optimal MR&R Actions	**0.906**	**0.749**	**0.730**

The optimization algorithm determined 109 bridges to receive MR&R actions, with the total agency cost of $14,342,844. The details of the optimal MR&R actions for these bridges can be found in Appendix C. In these results, all NHS bridges in district 3 that are selected to receive MR&R actions, as well as the description of the MR&R actions on their elements, the agency cost for performing these MR&R actions, and an estimation for the duration of the MR&R actions are shown. For illustration, a sample of such results is shown in Table 4-3.

Table 4-3- Sample of the suggested MR&R actions on NHS bridges in district 3, following the developed optimal budget allocation algorithm

Bridge SFN	**County-Route-SLM**	**Optimal Actions**	**Agency Cost on District (MR&R+AEM+MOT)**	**Estimated Project Duration (Days)**
2202344	ERI-00006-28834	Truss Steel(1), Gusset Plate Steel(1), Moveable Bearing (Roller/Sliding)(1), Replace Deck Items, Abutment Reinforced Concrete(2)	$1,706K	68
3902048	HUR-00061-18556	Replace Deck Items, Abutment Masonry(1)	$465K	15

(1): All portions of the element that are in condition-state 3 and 4 should be repaired to be improved to at least condition-state 2.

(2): All portions of the element that are in condition-state 3 and 4 should be repaired to be improved to at least condition-state 2, and, if applicable, those quantities of the element in condition-state 2 should receive maintenance/preservation actions.

In addition, a table is presented in Appendix C, which indicates the total agency cost of performing MR&R actions for different types of elements in district 3. Noticeably, these costs are calculated considering MR&R actions that are individually performed on those elements. According to this table, around 40% of the district budget is recommended for MR&R actions on steel protective coatings. Furthermore, 52 bridges (48%) among 109 bridges receiving MR&R action budgets (i.e. 11% of bridges among total NHS bridges in district 3) are found requiring MR&R actions for their reinforced concrete abutments. Interestingly, while the budget is limited, due to the significant reduction in the safety risks of district 3 NHS bridges, the algorithm suggests to replace three deck components. This contributes to approximately 16% of the budget.

4.5 Validation and verifications of the identified MR&R actions suggested by the developed optimal budget allocation program

As mentioned in Section 4.1, the optimal budget allocation algorithm systematically gives higher importance to bridges with higher safety concerns, and bridges with higher ADT and long detour length. To demonstrate these features, together with verification and validation of the results of the optimal budget allocation algorithm, two case studies are presented and discussed in this section. In the first case study, the optimization algorithm is implemented on eight sample Ohio bridges suggested by ODOT structure team. In this study, the sensitivity of optimal decisions are evaluated with respect to the variation of the ADT of a bridge (as a prominent serviceability feature), as well as the summary rating of a component of another bridge in the portfolio (as a major factor reflecting the safety of a bridge). In the second case study, four validation tests are conducted on the result of the optimal MR&R work plan for NHS bridges in district 3. This study is followed by the verification of the developed computer program through examining whether the program has selected the most optimal work plan for a simple network comprising two bridges from district 3.

Table 4-4- The specifications of the eight sample bridges used for the verification of the optimal budget allocation program

Inventory Bridge	**Structure File No.**	**Bridge Type**	**Deck Area (ft^2)**	**Year Built**	**No. of Spans**	**No. of lanes**	**Length (FT)**	**ADT**	**Detour length**	**General Appraisal**
DRIVE WAY over DRY RUN	2590271	PRESTRESSED CONCRETE/BOX BEAM/CONTINUOUS	3795	1992	3	2	110.0	50	99	7
US 33 over GEORGE CREEK	2502224	CONCRETE/ SLAB/CONTINUOUS	3339	1963	3	2	79.5	28,620	1	6
I 70 over HAGUE AVE	2504316	STEEL/BEAM/ CONTINUOUS	17696	1973	2	8	113.8	139,740	1	7
I 70 over FISHER RD	2504332	STEEL/BEAM/SIMPLE	17557	1973	1	8	120.7	139,740	1	6
I-70 over HARPER RD	2504510	STEEL/BEAM/ CONTINUOUS	5665	1973	3	2	132.3	31,970	1	6
I.R. 270 over CSX RR & PRIVATE RD	2513927	STEEL/BEAM/ CONTINUOUS	9612	1968	3	3	178.0	30,795	1	7
KENNY ROAD over TURKEY RUN	2568551	STEEL/CULVERT/ FILLED	676	1971	1	4	88.0	31,000	4	5
SR 4 NORTH over OVER CSX RR	5100127	PRESTRESSED CONCRETE/BOX BEAM/SIMPLE	27394	1967	16	2	805.8	3,511	0	6

4.5.1 Validation study on a sample of eight Ohio bridges

A realistic network of eight sample Ohio bridges is selected for the validation of the optimal budget allocation algorithm. Some structural and serviceability characteristics of these bridges are shown in Table 4-4. The bridges have various structural types and sizes. In addition, there is a distinct variation in the serviceability features of these bridges, such as ADT and detour length.

4.5.1.1 Sensitivity of the optimal allocated budgets to the variation of ADT

In this section, a marginal sensitivity analysis is performed to evaluate the sensitivity of the optimal allocated budget to the variation of ADT values of a sample bridge. I 70 over HAGUE AVE is selected as the sample bridge for this sensitivity study, since it has a high ADT value of 143,747 vehicle/day. Considering the traffic capacity of each lane to be 1750 vehicle/day (27), the current ADT of the bridge is about 43% of its traffic capacity.

Using the developed computer program, considering a budget limit of $400K, the optimal MR&R work plan for these eight bridges are identified and shown in Table 4-5. Results show that around $20,700 is allocated for repair actions on the deck and substructure of the I 70 over HAGUE AVE bridge. This budget improves elements within these components to a minimum safe and serviceable state (identified with a subscript of “min” in Table 4-5). It should be noted that the required budget to improve elements of each bridge to their minimum safe and serviceable state is also calculated and shown in the last column in Table 4-5.

If ADT of the bridge becomes a value as low as 10% of the traffic capacity of the lanes carried by the bridge, the allocated repair budget for this bridge becomes zero. Instead, the allocated repair budget for the I 70 over FISHER RD increases from $74,000 to $88,000. This shift in the allocated budget can be attributed to the fact that the enhancement in the network-level $OBCI_{current(risk-based)}$ achieved by repair actions on I 70 over HAGUE AVE bridge with low ADT is less than the improvement in the network-level $OBCI_{current(risk-based)}$ achieved by spending this money on I 70 over FISHER RD bridge with an ADT that is four times larger than the former bridge.

On the other hand, if the traffic demand for I 70 over HAGUE AVE bridge increases so that the ADT on the bridge becomes 80% of its traffic capacity, the allocated budget for repair activities remains unchanged for I 70 over HAGUE AVE bridge. This result is expected, since the code is designed in such a way that no more than the minimum safe and serviceable budget is allocated for any bridge in a network unless the budget limit for that network is more than the total required budget for performing minimum required repairs for all bridges in the network. As shown in Table 4-5, based on the calculations made by the developed computer program, the required budget for minimum required repairs for I 70 over HAGUE AVE bridge is $20,700, and the available budget for the network of the eight Ohio bridges is about 33% of the total required budget. As a result, based on safety considerations of the developed algorithm presented in Section 4.1, the assigned optimal budget for repair actions on I 70 over HAGUE AVE bridge, even after a significant increase in the ADT of the I 70 over HAGUE AVE bridge, remains the same (no more than the required budget for minimum required repairs on this bridge).

The result of this case study shows that the developed algorithm puts more emphasis on allocating repair budget for bridges with high ADT values.

Table 4-5- Sensitivity of optimal allocated budget for the eight sample bridges with the Variation of ADT for the I 70 over HAGUE AVE bridge

Inventory Bridge No.	**Optimal identified budget**			**Maximum assigned bridge-level budgets**
	10% ADT of the I-70 over Hague bridge traffic capacity	**Existing ADT (43% of the I-70 over Hague bridge traffic capacity)**	**80% ADT of the I-70 over Hague bridge traffic capacity**	
DRIVE WAY over DRY RUN	0	0	0	138,313
US 33 over GEORGE CREEK	0	0	0	260,149
I 70 over HAGUE AVE	**0***	**20,691****	**20,691****	**20,691**
I 70 over FISHER RD	88,133	73,871	73,871	112,618
I-70 over HARPER RD	0	0	0	48,062
I.R. 270 over CSX RR & PRIVATE RD	223,352	223,352	223,352	667,540
KENNY ROAD over TURKEY RUN	0	0	0	50,688
SR 4 NORTH over CSX RR	89,979	89,979	89,979	89,979
Sum of Bridges	401,464	407,893	407,893	1,389,171

*= $C^{0}_{\text{Approach}}, C^{0}_{\text{Deck}}, C^{0}_{\text{Superstructure}}, C^{0}_{\text{Substructure}}, C^{0}_{\text{Sign}}$

**= $C^{0}_{\text{Approach}}, C^{\text{min}}_{\text{Deck}}, C^{0}_{\text{Superstructure}}, C^{\text{min}}_{\text{Substructure}}, C^{0}_{\text{Sign}}$

4.5.1.2 Sensitivity of the optimal allocated budgets to the variation of component summary rating

In this section, a marginal sensitivity analysis is performed to evaluate the sensitivity of the optimal budget allocation to the variation of component summary ratings of a bridge among the eight sample bridges. For the purpose of verification, the result of this study shows how the developed optimal budget allocation algorithm responds to the variation of the safety of bridges, and whether these results are reasonable and justifiable. As elaborated in the Section 2.2.3, risk of improper functionality is directly affected by the summary ratings of bridge components. This risk cost affects $OBCI_{current(risk-based)}$ of bridges and the network, which subsequently impacts optimal allocation of repair budgets for bridges in the network.

The substructure of the SR 4 North bridge with an existing summary rating of 6 (i.e. “Satisfactory”) is selected for this marginal sensitivity analysis. In this bridge, substructure is the only component that has a condition worse than the minimum safe and serviceable state. As can be seen from Table 4-6, the maximum assigned budget for this bridge is $90,000. With the existing summary rating of the substructure of the SR 4 North bridge and the safety concerns associated with this rating, assigning maximum budget for repairs on this substructure component results in the most enhancement in the $OBCI_{current(risk-based)}$ of the network.

When summary rating of this component becomes 5, which shows a more severe safety-related condition, the same budget is allocated for this substructure. This is expected as no more money can be assigned for this bridge. On the other hand, when summary rating of the substructure is modified to 7, showing a less severe safety-related condition, the developed algorithm allocates no budget for the repair of the substructure component of the SR 4 North bridge. This result is also reasonable, as the priority of the allocated budget is shifted to components from other bridges, in this example, to the I-70 over HARPER RD bridge that has a higher probability of incomplete functionality and/or broader safety-related consequences due to large cost of repairs and high ADT values, among others.

Table 4-6- Sensitivity of optimal allocated budget for the eight sample bridges with the Variation of component summary rating of the substructure component of the I 70 over HAGUE AVE bridge

Inventory Bridge No.	**Optimal identified budget**			**Maximum assigned bridge-level budgets**
	Summary rating of 5 for the substructure of SR 4 North bridge	**Existing summary rating for the substructure (i.e. 6) of SR 4 North bridge**	**Summary rating of 7 for the substructure of SR 4 North bridge**	
DRIVE WAY over DRY RUN	0	0	0	138,313
US 33 over GEORGE CREEK	0	0	0	260,149
I 70 over HAGUE AVE	20,691	20,691	20,691	20,691
I 70 over FISHER RD	73,871	73,871	112,618	112,618
I-70 over HARPER RD	0	0	48,062	48,062
I.R. 270 over CSX RR & PRIVATE RD	223,352	223,352	223,352	667,540
KENNY ROAD over TURKEY RUN	0	0	0	50,688
SR 4 NORTH over CSX RR	**89,979****	**89,979****	**0***	**89,979**
Sum of Bridges	407,893	407,893	404,724	1,389,171

*= $\mathrm{C}^{0}_{\mathrm{Approach}}, \mathrm{C}^{0}_{\mathrm{Deck}}, \mathrm{C}^{0}_{\mathrm{Superstructure}}, \mathrm{C}^{0}_{\mathrm{Substructure}}, \mathrm{C}^{0}_{\mathrm{Sign}}$

**= $\mathrm{C}^{0}_{\mathrm{Approach}}, \mathrm{C}^{0}_{\mathrm{Deck}}, \mathrm{C}^{0}_{\mathrm{Superstructure}}, \mathrm{C}^{\mathrm{min}}_{\mathrm{Substructure}}, \mathrm{C}^{0}_{\mathrm{Sign}}$

4.5.2 Verification and validation of the identified MR&R actions for the NHS bridges in district 3 of Ohio

Using the results of the first set of optimal MR&R work plan for the 484 NHS bridges of district 3, authors conducted in-depth validation studies for the proposed algorithm. For this purpose, the research team evaluated the effectiveness of multiple factors in the assigned budgets.

4.5.2.1 Evaluation of the priority of selecting repair alternatives with high benefit-to-cost ratios in the optimal work plan

According to the formulation of the optimal budget allocation algorithm, presented in Equation (4-4), if the agency’s budget is less than the required cost to improve all bridges to their like-new state (which commonly happens), bridges that bring the most possible benefit to the network will be selected for optimal repairs. This maximum benefit is achieved when the incurred user and agency risk costs to reach to the like-new state of bridges after the MR&R work plan is minimized. Generally, while not always true, the following relationship holds for any bridge *B*:

$$\begin{aligned}&(AC_B^{Ln} + UC_B^{Ln})_{Before\ any\ work\ plan}\\&\qquad \approx (AC_B + UC_B)_{Due\ to\ an\ MR\&R\ work\ plan} + (AC_B^{Ln} + UC_B^{Ln})_{After\ the\ work\ plan}\end{aligned} \tag{4-7}$$

According to Equation (4-7), the benefit can be considered as $(AC_b + UC_b)_{Due\ to\ an\ MR\&R\ work\ plan}$. When the budget limit is low, to minimize the required user and agency risk costs to reach to the like-new state for any bridge *B* after the MR&R work plan, i.e. $(AC_b^{ln} + UC_b^{ln})_{After\ the\ work\ plan}$, the optimization code generally should select repair plans that have the maximum benefit to cost ratio of

$\frac{(AC_b+UC_b)_{Due\ to\ an\ MR\&R\ work\ plan}}{(AC_b)_{Due\ to\ an\ MR\&R\ work\ plan}}$, while fitting in the available budget. This assures that the spent money reduces the remaining cost of the network to the largest extent.

On this basis, first, a graph is shown in Figure 4-3 that shows the frequency of various ranges of $\frac{(AC_b+UC_b)_{Due\ to\ an\ MR\&R\ work\ plan}}{(AC_b)_{Due\ to\ an\ MR\&R\ work\ plan}}$ for repair work plans on bridges that are identified by the optimal budget allocation algorithm. Hereafter, the ratio $\frac{(AC_b+UC_b)_{Due\ to\ an\ MR\&R\ work\ plan}}{(AC_b)_{Due\ to\ an\ MR\&R\ work\ plan}}$ is referred to as *benefit to cost ratio*. Notably, based on the formulation of $OBCI_{current(risk-based)}$ (see Equation (2-4)) at bridge-level, this ratio is accurately calculated for any bridge *B* as follows:

$$\frac{(AC_B + UC_B)_{Due\ to\ an\ MR\&R\ work\ plan}}{(AC_B)_{Due\ to\ an\ MR\&R\ work\ plan}} = \frac{\left(OBCI_{current(risk-based)}^{After\ the\ work\ plan} - OBCI_{current(risk-based)}^{Before\ the\ work\ plan}\right) \times \left(AC_B^{Rep} + UC_B^{Rep}\right)}{(AC_B)_{Due\ to\ an\ MR\&R\ work\ plan}} \tag{4-8}$$

In order to evaluate whether bridge-level work plans with maximum benefit to cost ratios are selected in the optimal work plan of the network, a bar chart plot is presented and shown in Figure 4-3. The chart shows the percentage of bridges among all 484 bridges that are selected to receive optimal work plans in various ranges of benefit to cost ratios. It should be noted that out of 484 bridges, only 253 bridges have work plan combinations, among which the optimization code should identify the optimal plans. Bridges that have no repair work plan combinations, i.e. 231 bridges, are in a condition better than or equal to their minimum safe and serviceable state with $\mathrm{GA} \geq 6$. For the 253 candidate bridges in this district, the representative benefit to cost ratios in Figure 4-3 are considered as the ones with the largest value of benefit to cost ratio among all work plan combinations of each bridge. For instance, if a bridge has three different work plan combinations for its elements, with benefit to cost ratios of 3.5, 7.6, and 5.4, and a work plan from these three are identified optimal by the optimization code, 7.6 is considered as the benefit to cost ratio for this bridge.

Noticeably, out of the 109 selected bridges by the optimization algorithm, 54 have more than or equal to two variations of repair work plans with different benefit to cost ratios. The identified optimal repair works plan for as high as 46 of these 54 bridges have the highest benefit to cost ratios among all possibilities of repair work plans for each of these bridges. It is worthy to mention that one potential reason for the 8 (out of 109) bridges that are selected with a work plan having a benefit to cost ratio less than the maximum value, is due to the limitation in the available budget.

Adding the 55 other bridges with only one optimal repair work plan, it can be claimed that for 101 out of 109 bridges identified by the optimization code, the work plans with the highest benefit to cost ratios are selected. This is equal to 93% of the selected bridges. Thus, considering the maximum benefit to cost ratio of work plan combinations for optimally selected bridges is relatively accurate with only 7% error. On this basis, Figure 4-3 shows the frequency of bridges with various ranges of these benefit to cost ratios that are selected to receive optimal MR&R work plans. As expected, the code has selected all bridges in the 9 out of 10 highest categories of benefit to cost ratios. This shows the effectiveness of the code in selecting bridges with the highest benefit to cost ratios as optimal decisions for a district. As a result, the highest possible network-level $OBCI_{current(risk-based)}$ for district 10 is achieved, as well.

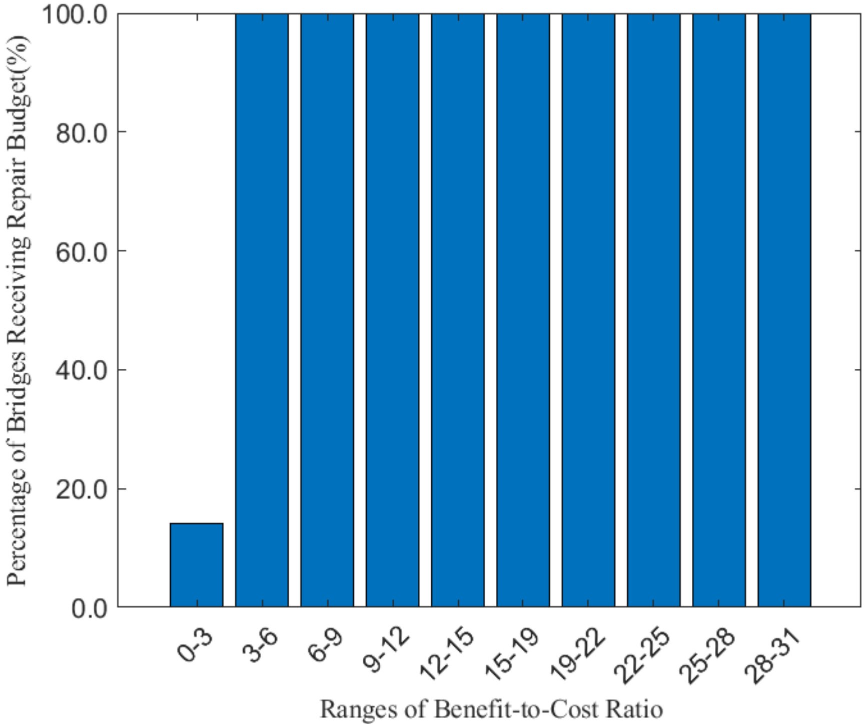


Figure 4-3- Percentage of bridges among all 484 bridges that are selected to receive optimal work plans in various ranges of benefit to cost ratios.

4.5.2.2 Evaluation of the priority of selecting bridges with low $OBCI_{current(risk-based)}$ and GA in the optimal work plan

According to the formulation of $OBCI_{current(risk-based)}$, bridges with lower $OBCI_{current(risk-based)}$ values are likely to have more safety-related costs, which can be alleviated with a repair cost that is relatively small compared to those safety consequences. That is, it is likely that large benefit to cost ratios can be gained if these bridges are repaired; thus, it is likely that these bridges are selected in the list of the optimal work plan. Additionally, since safety-related costs of bridges are directly correlated with GA values, it is generally expected that bridges with lower GA values should be selected in the list of optimal work plan.

Figure 4-4 shows the percentage of bridges in various ranges of $OBCI_{current(risk-based)}$ that are identified to receive optimal repairs. A similar result is plotted for various ranges of GA in Figure 4-5. As expected, there is a meaningful correlation between $OBCI_{current(risk-based)}$ of a bridge, as well as its GA, and the assigned budget for MR&R actions for that bridge. Generally, the percentage of bridges with lower $OBCI_{current(risk-based)}$ and GA values that receive optimal budget are large and this ratio decreases as $OBCI_{current(risk-based)}$ or GA of the bridges increases. However, a more refined trend can be extracted from the $OBCI_{current(risk-based)}$ curve compared to the GA plot with only 5 meaningful categories (i.e. GA of 4~8). This indicates the superiority of $OBCI_{current(risk-based)}$ if an index is planned to be solely used for optimal MR&R decision-making.

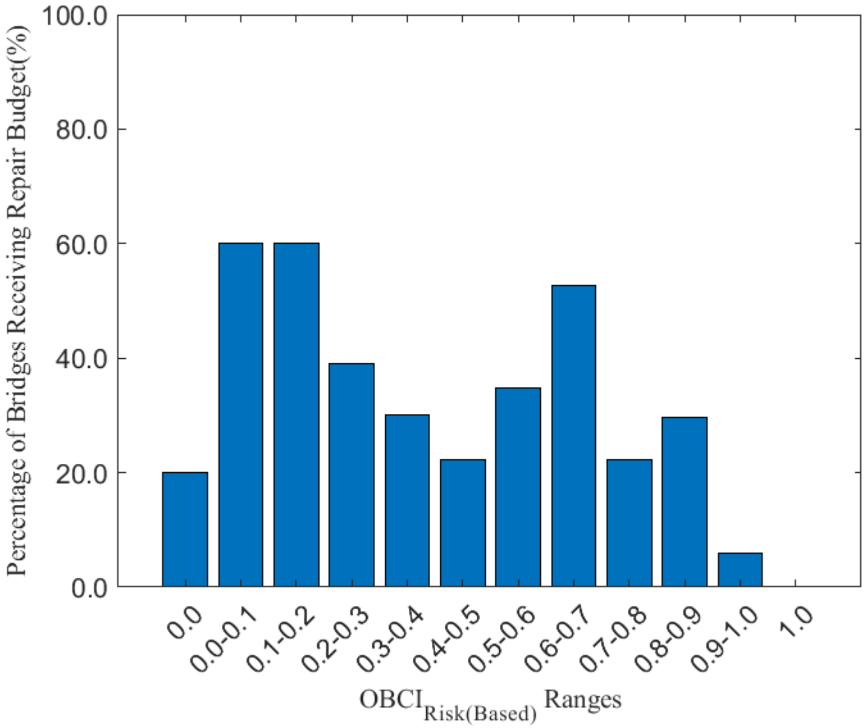


Figure 4-4- Percentage of bridges in various ranges of $OBCI_{current(risk-based)}$ that are identified to receive optimal repairs

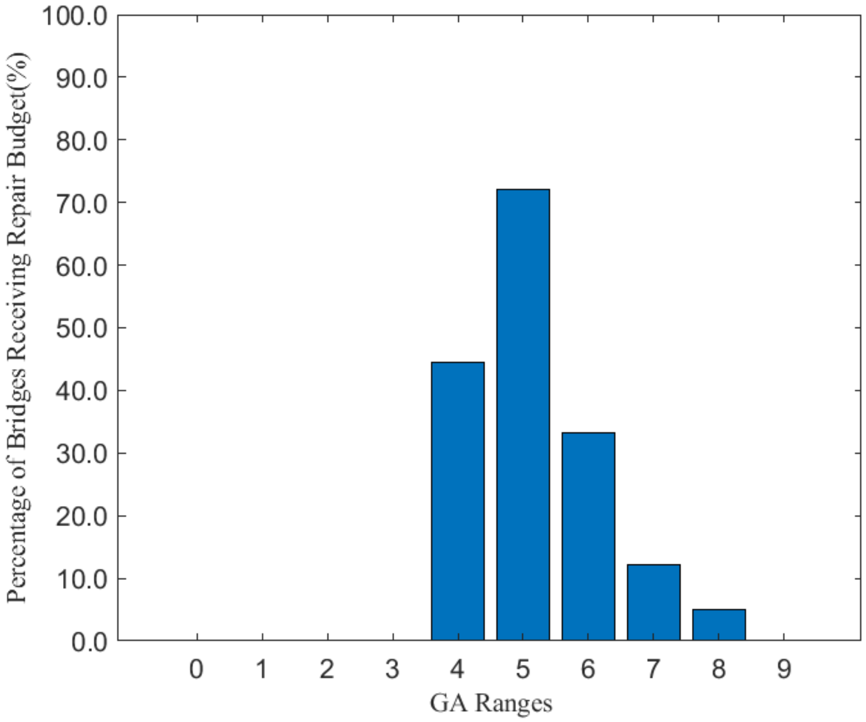


Figure 4-5- Percentage of bridges in various ranges of General Appraisal (GA) that are identified to receive optimal repairs

4.5.2.3 Evaluation of the priority of selecting bridges with high ADT and detour length combined with low $\boldsymbol{OBCI_{current(risk-based)}}$ in the optimal work plan

As mentioned in the previous section, generally, bridges with lower $OBCI_{current(risk-based)}$ values have larger risk costs due to their larger probability of improper functionalities. Often, these costs can be prevented by spending small budget on defected elements that are in condition-state 3 and 4. As a result, large benefit is achieved in terms of the reduction in the required risk cost to improve the bridge to its like-new state. Thus, the optimization code is expected to generally select such bridges. This was also shown in Figure 4-4.

The same condition holds for bridges with high ADT and/or long detours, which incur large user costs if repair actions are required to improve them to their like-new state. Due to large user costs, the total costs of repairing these bridges become relatively close to the their replacement cost, which generally results in small values of $OBCI_{current(risk-based)}$. For these bridges, agency costs of repair actions are often considerably less than the incurred user costs as a result of performing those repairs. This is equivalent to a large benefit to cost ratio for such repair actions on these bridges. Therefore, the optimal budget allocation algorithm generally gives higher priority to bridges with high values of ADT and/or long detours.

A color-coded 3-D plot is shown in Figure 4-6, which shows the percentage of bridges that are identified to receive optimal MR&R actions versus various ranges of $OBCI_{current(risk-based)}$ and the product of ADT and the detour length (as user cost is linearly proportionate to these factors). The results in this figure indicate that as a general trend, bridges with lower values of $OBCI_{current(risk-based)}$ and higher values of the product of ADT and the detour length have more priority to receive budget for MR&R actions, as these actions result in more enhancement in the performance of the network. This priority becomes more significant for very large values of the product of ADT and the detour length.

The significance of user cost in optimal decisions is also shown in Figure 4-7. In this figure, a marginal graph for the percentage of bridges that are identified to receive optimal MR&R actions, versus various ranges of the product of ADT and the detour length is plotted. The result of this figure also confirm the priority of work plans for bridges with high ADT and long detours.

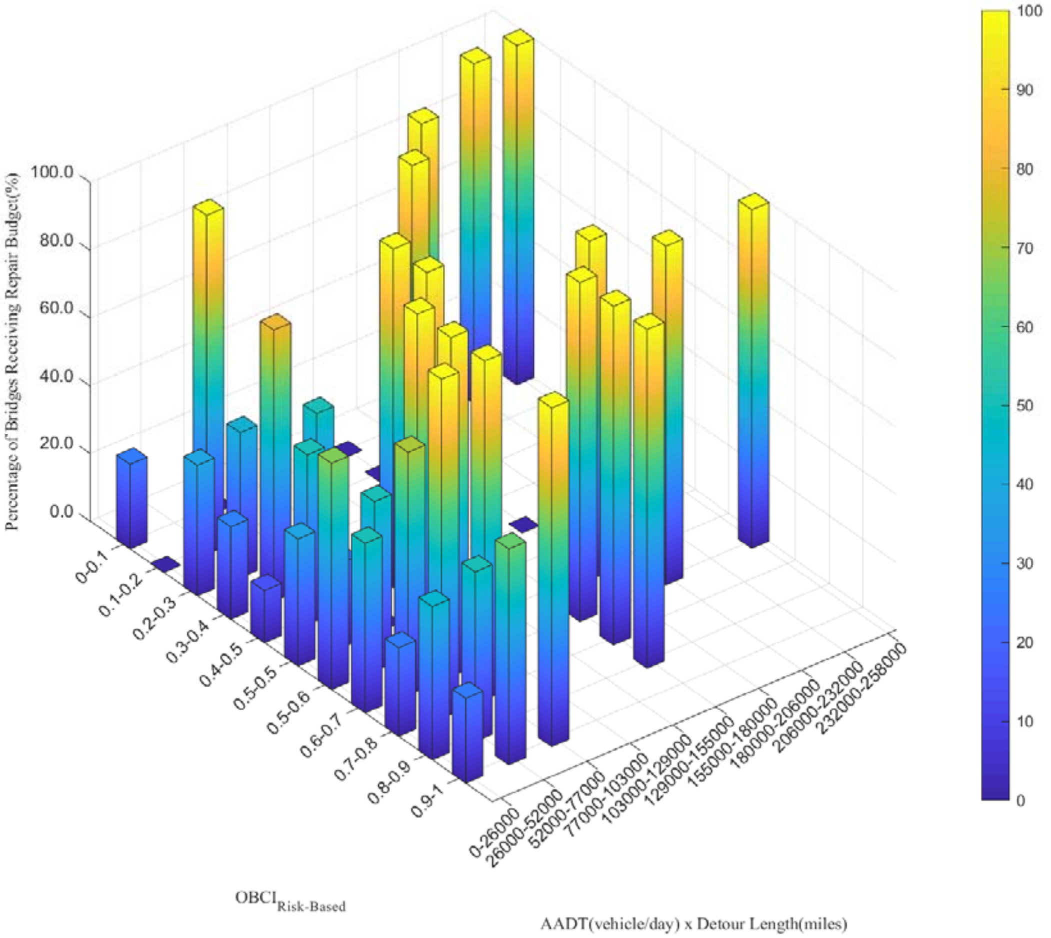


Figure 4-6- Percentage of bridges that are identified to receive optimal MR&R actions, versus various ranges of $OBCI_{current(risk-based)}$ and the product of AADT and the detour length.

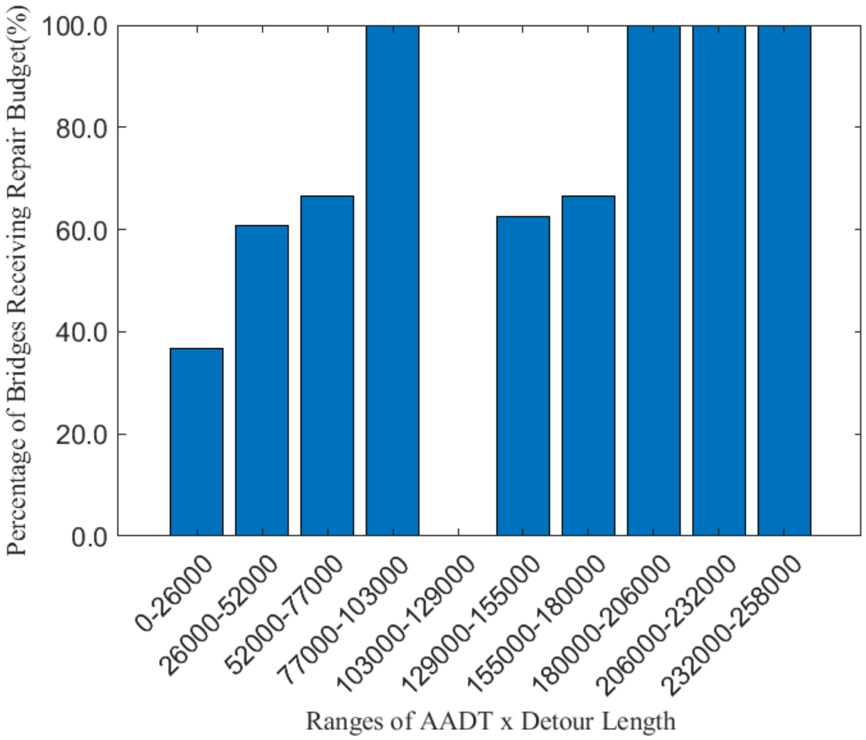


Figure 4-7- Percentage of bridges that are identified to receive optimal MR&R actions, versus various ranges of the product of AADT and the detour length.

4.5.2.4 Evaluation of the priority of selecting bridges with safety concerns in the optimal work plan

Comparing the formulations of $OBCI_{current}$ and $OBCI_{current(risk-based)}$ at bridge-level, it can be stated that a large difference between these two values implies safety concerns for the bridge. As mentioned before, these safety concerns can often be addressed by spending relatively low budget; resulting in a significant reduction in the incurred agency and user cost for the network to reach to its like-new state. Thus, on a general basis, the optimization code is expected to select bridges with a large difference between their bridge-level $OBCI_{current}$ and $OBCI_{current(risk-based)}$. This feature is demonstrated in Figure 4-8. According to this plot, there is an increasing trend in the percentage of bridges that are identified to receive optimal MR&R actions with the ratio of $OBCI_{current}$ to $OBCI_{current(risk-based)}$.

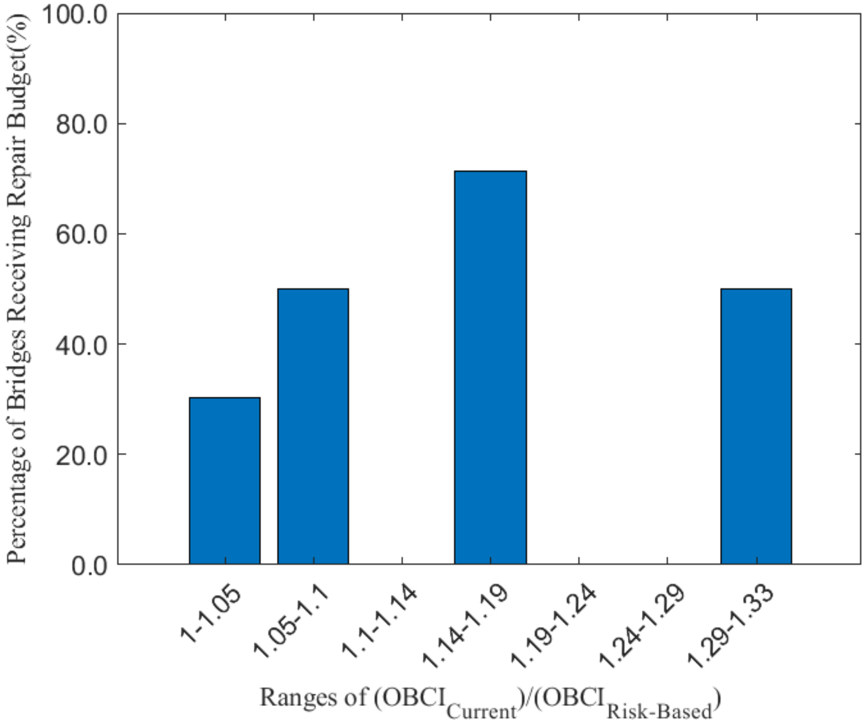


Figure 4-8- Percentage of bridges that are identified to receive optimal MR&R actions, versus various ranges of $OBCI_{current}/OBCI_{current(risk-based)}$.

4.5.2.5 Verification of the developed computer program for identifying the most optimal work plan for a sample NHS bridge

In this study, the research team selected two sample bridges from the NHS bridges of district 3 to verify the developed computer code for the optimal budget allocation algorithm. The purpose is to check whether the computer code identifies the most optimal MR&R work plan among all possibilities such that the network-level $OBCI_{current(risk-based)}$ is maximized. General information of the two selected bridges are given in Table 4-7.

Table 4-7-General information of the two selected bridges for the verification of the developed optimization code

Structure File No.	County-Route-SLM	Year built	No. spans	No. lanes on	Traffic direction	Deck area(ft^2)	ADT	Detour length(mi)	General Appraisal
0300306	'ASD-00030-00980'	1966	3	2	1	6269	6196	1.24	6
7001118	'RIC-00030-10738'	1957	3	4	2	15113	33905	1.24	5

Based on the 2017 excel file of the NBE information of ODOT NHS bridges (which is explained in detail in Appendix D), the element-level inspection report of these bridges are shown in Table 4-8 and Table 4-9.

Table 4-8- Element-level inspection report of the bridge with SFN 0300306

Element	Unit	QTY	Condition-State			
			CS1	CS2	CS3	CS4
Deck Items						
Reinforced Concrete Deck	SF	6276	0	6276	0	0
Strip Seal Expansion Joint	LF	107	1	106	0	0
Reinforced Concrete Bridge Railing	LF	299	299	0	0	0
Deck Summary	-	6				
Superstructure Items						
Girder/Beam Steel	LF	894	894	0	0	0
Elastomeric Bearing	Each	24	24	0	0	0
Steel Protective Coating	SF	9332	9332	0	0	0
Superstructure Summary	-	8				
Substructure Items						
Columns Reinforced Concrete	Each	8	8	0	0	0
Abutment Reinforced Concrete	LF	107	64	43	0	0
Pier Cap Reinforced Concrete	LF	107	107	0	0	0
Substructure Summary	-	7				

Table 4-9- Element-level inspection report of the bridge with SFN 7001118

Element	Unit	QTY	Condition-State			
			CS1	CS2	CS3	CS4
Deck Items						
Reinforced Concrete Deck	SF	15120	2866	12254	0	0
Strip Seal Expansion Joint	LF	210	1	207	2	0
Metal Bridge Railing	LF	394	197	197	0	0
Wearing Surfaces	SF	13199	12935	132	132	0
Deck Summary	-	5				
Superstructure Items						
Girder/Beam Steel	LF	2352	0	2210	118	24
Moveable Bearing (Roller/Sliding)	Each	48	0	36	12	0
Steel Protective Coating	SF	30581	1	0	3058	27522
Superstructure Summary	-	6				
Substructure Items						
Columns Reinforced Concrete	Each	14	4	3	7	0
Abutment Reinforced Concrete	LF	210	43	157	10	0
Pier Cap Reinforced Concrete	LF	210	210	0	0	0
Substructure Summary	-	5				

OBCI values for the case study bridges are calculated according to the developed computer code and shown in Table 4-10 and Table 4-11. Notably, $OBCI_{current}$ and $OBCI_{current(risk-based)}$ of the “Reinforced Concrete Deck” element and the deck component of the bridge with SFN 0300306 are identical. The reason is that all elements of the deck component, except for the “Reinforced Concrete Deck” are in their like-new condition; i.e. requiring no repairs. In addition, due to the large area of the “Reinforced Concrete

Deck" compared to the quantities of other elements of the deck component, the cost of replacing the bridge "Reinforced Concrete Deck" element is significantly larger (almost 10 times) compared to the replacement cost of other elements of the deck component. For this reason, considering the reduction in the replacement costs due to replacing the entire component, the replacement cost of the deck component is found identical to the cost of replacing the "Reinforced Concrete Deck" element alone. These result in identical $OBCI_{current}$, $OBCI_{current(risk-based)}$ for the "Reinforced Concrete Deck" element and the deck component.

In addition, $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ of the "Girder/Beam Steel" element of the bridge with SFN 7001118 are computed as zero. The reason lies in the fact that, based on the available cost tables, there are no actions for the repair of the quantities of a steel girder in condition-state 4, except for replacing the entire girders. Thus, the repair and replacement cost of this element become identical, leading to zero values for all OBCI values of this element.

Table 4-10- OBCI values for the bridge with SFN 0300306

OBCI	$OBCI_{min}$	$OBCI_{current}$	$OBCI_{current(risk-based)}$
Bridge-level			
Bridge with SFN of 0300276	1.000	0.846	0.793
Component-level			
Deck	1.000	0.698	0.618
Superstructure	1.000	1.000	1.000
Substructure	1.000	0.985	0.961
Element-level			
Reinforced Concrete Deck	1.000	0.698	0.618
Strip Seal Expansion Joint	1.000	1.000	1.000
Reinforced Concrete Bridge Railing	1.000	1.000	1.000
Girder/Beam Steel	1.000	1.000	1.000
Elastomeric Bearing	1.000	1.000	1.000
Steel Protective Coating	1.000	1.000	1.000
Columns Reinforced Concrete	1.000	1.000	1.000
Abutment Reinforced Concrete	1.000	0.908	0.795
Pier Cap Reinforced Concrete	1.000	1.000	1.000

Table 4-11- OBCI values for the bridge with SFN 7001118

OBCI	$OBCI_{min}$	$OBCI_{current}$	$OBCI_{current(risk-based)}$
Bridge-level			
Bridge with SFN of 7001118	0.575	0.377	0.324
Component-level			
Deck	1.000	0.703	0.541
Superstructure	0.298	0.183	0.165
Substructure	0.959	0.928	0.626
Element-level			
Reinforced Concrete Deck	1.000	0.599	0.426
Strip Seal Expansion Joint	1.000	0.830	0.830
Metal Bridge Railing	1.000	0.588	0.588
Wearing Surfaces	1.000	0.970	0.970
Girder/Beam Steel	0.000	0.000	0.000
Moveable Bearing (Roller/Sliding)	0.826	0.446	0.446
Steel Protective Coating	0.005	0.005	0.004
Columns Reinforced Concrete	0.866	0.781	0.304
Abutment Reinforced Concrete	0.920	0.803	0.320
Pier Cap Reinforced Concrete	1.000	1.000	1.000

Based on the cost calculations of the OBCI framework, the minimum required cost to have all the elements of the two sample bridges in their minimum safe and serviceable state is $1.5 Million. This budget is called “minimum required budget”. The maximum required cost to improve all elements of these two bridges to their like-new state is also calculated as $2.0 Million. This budget is called “maximum required budget” in this report. In the rest, the capability of the developed optimal budget allocation program in identifying the most optimal MR&R work plan is evaluated considering a budget limit of $500K.

The considered maximum budget is less than the minimum required budget for the portfolio of the two bridges. For this reason, based on the explanations provided in Section 4.1, no improving actions should be considered for components with $OBCI_{min} = 1$ and summary rating greater than or equal to 6. Additionally, for elements with an $OBCI_{min} < 1$ belonging to components with a summary rating greater than or equal to 6, the optimization program only considers MR&R actions that improve their condition to their minimum safe and serviceable state. When the summary rating of a component is less than 6 and $OBCI_{min}$ of all elements in that component are equal to one (e.g. the deck component in the bridge with SFN 7001118), the code considers repair/maintenance actions that improve the condition of those elements to their like-new state. This type of action will address the safety concerns through increasing the summary rating of the component.

As explained in Section 4.1, for practicality, optimal actions are considered at component-level. That is, either

- All elements of a component, rather than just one, with $OBCI_{min} < 1$ are repaired to be improved to their minimum safe and serviceable state, through repairing all portions of the element that are in condition-state 3 and 4, so that these portions will improve to at least condition-state 2, or
- All elements in that component are improved to their like-new state, through repairing all portions of the element that are in condition-state 3 and 4, so that these portions will improve to at least condition-state 2, together with maintaining/preserving those portions in condition-state 2, or

- The component will be replaced, or
- No action will be performed.

In this section, these action are defined with the numbers (1), (2), (3), and (0), respectively. If the replacement cost of the component is less than the sum of repair/maintenance actions of all elements in that component, the computer code automatically considers the replacement cost of the component. Similar analysis is also conducted by the computer program to determine whether the cost of bridge replacement is less than repair/maintenance costs of all components of the bridge. If the latter cost is more, bridge replacement will be considered for that action possibility.

Table 4-12- The list of all possible set of actions for each of the two sample bridges, considering a budget limit less than the minimum required budget for the network

Bridge SFN	**Action Possibility index**	**Actions Possibilities**	**Agency Cost***	**Reduction in the Required Agency and User Costs** to the Like-New State (Benefit)**
0300306	B1-1	Deck (0), Superstructure (0), Substructure (0)	$0K	$0K
7001118	B2-1	Deck (0), Superstructure (0), Substructure (0)	$0K	$0K
	B2-2	Deck (2), Superstructure (0), Substructure (0)	$301K	$1,933K
	B2-3	Deck (0), Superstructure (1), Substructure (0)	$2,140K	$3,844K
	B2-4	Deck (2), Superstructure (1), Substructure (0)	$2,324K	$5,911K
	B2-5	Deck (0), Superstructure (0), Substructure (1)	$55K	$148K
	B2-6	Deck (2), Superstructure (0), Substructure (1)	$328K	$2,625K
	B2-7	Deck (0), Superstructure (1), Substructure (1)	$2,140K	$244K
	B2-8	Deck (2), Superstructure (1), Substructure (1)	$2,349K	$7,708K

* Agency Cost= MR&R+AEM+MOT
** Agency and User Cost= MR&R+AEM+MOT+DVE
(0): No action on elements of the component.
(1): All portions of the elements in the component that are in condition-state 3 and 4 should be repaired to be improved to at least condition-state 2.
(2): All portions of the elements in the component that are in condition-state 3 and 4 should be repaired to be improved to at least condition-state 2, and, if applicable, those quantities of the element in condition-state 2 should receive maintenance/preservation actions.

Table 4-12 shows the list of all possible set of actions for each of the two sample bridges. Furthermore, this table shows the required agency cost (MR&R+AEM+MOT) for these work plans, as well as the corresponding reduction in the required agency and user costs to the like-new state (i.e. benefit). As shown in this table, no action possibility is identified for the bridge with SFN 0300306, since $OBCI_{min}$ of this bridge is one and no component with a summary rating less than or equal to 5 exists in this bridge.

For the bridge with SFN 7001118, the most benefits are generally achieved when repair/maintenance actions are conducted on the deck. Two reasons can be mentioned for this observation: 1) According to the developed computer program, the required duration for the repair of the deck is about twice, and ten times the required time for the repair of superstructure and substructure elements, respectively. Given the large traffic volume passing on this bridge, large user costs are incurred when the deck is improved to or is close to its desired state, i.e. like-new or minimum safe and serviceable states. Thus, if such repairs are performed, the total incurred repair costs to improve the bridge to its like-new state will be considerably reduced, resulting in large benefits for deck repairs. In addition, 2) the summary rating of the deck is 5. Together with the substructure, this value is the lowest rating in bridge components. Improving this value by repair activities reduces the risk costs considerably, which results in large benefits.

Only one work plan needs to be selected for each bridge. Given the action possibilities in Table 4-12, the only action for the bridge with SFN 0300306 is to do nothing for all elements of this bridge. However, there are eight different possibilities for the other bridge with SFN 7001118. As explained before, the optimal work plan maximally reduces the required agency and user costs to reach the like-new state of the network after conducting that work plan; this is the objective of the developed optimal budget allocation algorithm. According to Table 2-12, the most reduction is incurred by the B2-8 action possibility for the second bridge. However, the required budget for this action, $1,752K, is more than the agency's considered available budget of $500K. Sorting based on the amount of reduction in the required user and agency costs (which can be called benefits), the most beneficial action that fits the available budget is B2-6, which is highlighted in Table 4-12. After evaluating the developed computer code, work plan B2-6 was also determined as the optimal work plan by this computer program.

5. Conclusions and future directions

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

- Objectively incorporates a comprehensive list of 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.
- Effectively utilizes ODOT's bridge inventory and inspection databases.

OBCI is a cost-based index that ranges from zero to one and represents the performance of bridges at element-, component-, bridge-, and network-levels. Effects of serviceability and safety features of bridges are incorporated in this index through a broad set of direct and indirect consequences of various bridge conditions using the unified metric of cost. Three variations of OBCI are suggested, $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$. In $OBCI_{min}$ the proximity of the system to minimum acceptable conditions for its constituent elements is evaluated. 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. $OBCI_{current}$ compares the current condition of the system to the like-new condition of the system. Similarly, the costs to improve all elements of the system to their like-new state is compared with the incurred cost to replace the system. With the performance objective of reaching like-new state, $OBCI_{current(risk-based)}$ quantitatively accounts for safety risks associated with severity, extent, location, and pattern of defects for major bridge elements.

To demonstrate the features and capabilities of OBCI, the applications of $OBCI_{min}$ and $OBCI_{current}$ are shown for a number of bridges in Ohio. The inspection report, as well as information regarding configuration, type and the traffic flow of these bridges are provided by ODOT. The calculated $OBCI_{min}$ for these bridge identified bridges, components, and elements that require immediate repairs due to not meeting the minimum acceptable condition-state thresholds. The results of $OBCI_{current}$ also objectively determine elements and components with poor performance that require improving actions to reach their like-new state. Additionally, it is shown that $OBCI_{min}$ and $OBCI_{current}$ can be considerably beneficial in estimating the costs of bridge members to reach their minimum acceptable and like-new states, respectively. Based on these features, appropriate work plan alternatives can be found, and the best considering the incurred cost, as well as the enhancement in the OBCI performance 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. Thus, ODOT and other agencies can utilize OBCI, not only to objectively evaluate the performance of their bridges, but also to identify appropriate work plans that enhance the safety and serviceability of their bridges.

In addition, calculation of $OBCI_{current(risk-based)}$ at element-, component- and bridge-level show that this index successfully identifies bridges, components, and elements with safety concerns by showing relatively low values when such concerns exist. Furthermore, through $OBCI_{min}$ and $OBCI_{current}$ values, which disregard safety concerns, the required costs for the repair of those deficiencies to meet minimum acceptable conditions or the like-new state can be separately estimated. Thus, these three indices can be employed to assist with risk-informed bridge management and budget estimation.

A systematic module-based computer program is also developed to automatically take as input element-level inspections and appraisal information of the entire ODOT's National Highway System (NHS) bridges, and calculate $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ for bridges in Ohio districts.

This computer program is utilized to calculate $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ for the 228 NHS bridges in district 10. Multiple bar chart plots are created to show the various information that these indexes provide. Based on the data from 2017, the required agency cost, as well as the incurred user and agency costs to improve all bridges to the minimum acceptable conditions, as well as their like-new states, are separately calculated. Furthermore, $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ of this district are computed as 0.835, 0.666, and 0.649, respectively. Similar cost and OBCI analyses are performed at bridge- and component-level, as well. These results show that around 50% of bridges are at their minimum acceptable conditions. Additionally, based on the results of $OBCI_{current(risk-based)}$, which includes safety risks in addition to other costs, culverts with around 30%, and substructures with around 80% having $OBCI_{current(risk-based)} \geq 0.9$ are found to be the most critical, and the safest among components, respectively. These results can assist ODOT with targeted planning for their bridges or bridge components in large portfolios. For instance, a target of $OBCI_{min}$ of 90% can be set as a goal for the entire district.

Finally, based on $OBCI_{current(risk-based)}$ and implementing a mixed-integer linear programing, a systematic optimal budget allocation algorithm is developed that identifies the optimal Maintenance, Repair, and Replacement (MR&R) work plan for NHS bridges of ODOT's districts. Considering a maximum available budget, this algorithm determines optimal actions at element-level such that the network-level $OBCI_{current(risk-based)}$ of the district is maximized. As demonstrated, this objective is equivalent to minimizing annual safety risks of bridges and the serviceability interruptions on users due to repair actions on these assets.

Through a computer program developed in this project, the optimization framework is employed for identifying optimal MR&R actions for the 484 NHS bridges in district 3 of Ohio considering a budget of $14,350,000. Based on the data from 2017, the optimization algorithm determines 109 bridges to receive MR&R actions. According to these results, around 40% of the district budget is recommended for MR&R actions on steel protective coatings. Furthermore, 52 bridges among 109 bridges receiving MR&R action budgets are found requiring MR&R actions for their reinforced concrete abutments. Interestingly, while the budget is limited, due to the significant reduction on the safety risks of district 3 NHS bridges, the algorithm suggested to replace three deck components. This accounts for approximately 16% of the district's budget. Through several validation and verification tests, the ability of the algorithm to systematically prioritize work plans that reduce safety risks of bridges, and to bridges with high ADT and long detour length are demonstrated.

ODOT districts and other state DOTs can take advantage of the developed budget allocation program to systematically identify optimal MR&R actions on their bridges such that the safety and serviceability, and in general, the performance of their bridge portfolios are maximized. A graphical software application of the optimal budget allocation framework is also developed, which enables a user-friendly interaction with the computer program. As a suggestion for the future, the OBCI and optimization framework can be enhanced through incorporation of the effect of deterioration in bridge elements.

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Appendix A: Critical review of bridge performance measures

In this section, some of the most commonly used to recently proposed performance measures are explained. These include metrics proposed/implemented by state DOTs, FHWA, NCHRP, and other researchers in the U.S. and around the world. It is noteworthy that the following literature review is also published in (1).

National Bridge Inventory (NBI)

In 1967, Silver Bridge over Ohio River collapsed without any warning and resulted in 46 fatalities. The reason was later identified as corrosion in an eyebar link of the bridge (2). This catastrophic event led FHWA to mandate all states to provide information about each and every bridge in their inventory, in order to generate a National Bridge Inventory (NBI). On this basis, the Federal Highway Administration later introduced a bridge element rating guideline based on the physical condition of elements (3). At element level, FHWA requires all states to provide an inventory for the condition-states of their bridge elements to generate the nationwide NBI rating. NBI rating for decks, superstructures, substructures, culverts and sub-elements are presented as integer states ranging from 0 (worst condition) to 9 (as-new condition) (Items #58 to #62 in (3)). This rating provides qualitative assessments for the collective physical condition of components of the same type, e.g. superstructures (3).

In the State of Ohio, NBI condition ratings are provided for floor, wearing surface, and the paint conditions. In addition, a general NBI rating called general appraisal is defined as the lowest NBI ratings of deck, superstructure, substructure, and culvert components. NBI rating is commonly used directly for the management of bridges by setting target values for various bridge components. Delaware also requires at least 75% of bridges to have NBI ratings above 6 for the combined deck, superstructure and substructure components, while state of Washington has set the goal to have at least 95% of its bridge decks, superstructures and substructures to exceed “good” or “fair” condition rating (4). Furthermore, NBI ratings have provided a foundation for many other performance measures such as sufficiency rating, structural deficiency, and functional obsolescence.

Geometric Rating (GR)

Geometric rating (GR) is a measure of bridge geometric properties that affect the serviceability of bridges. GR is evaluated based on NBI ratings for deck geometry, vertical and horizontal underclearance, waterway adequacy, and approach road alignment (5). The rating for deck geometry takes into account bridge width, average daily traffic (ADT), the number of lanes on the bridge, whether the bridge is one-way or two-ways, and functional classifications. Underclearance rating considers vertical and horizontal underclearances which are measured as the distance from the through roadway to the closest component of the bridge. Approach alignment rating is evaluated based on deficiencies that may exist due to alignment disparities between the approach roadway and the bridge spans. Ratings for each of these metrics range from 0 to 9 representing the worst and best conditions, respectively. Ratings for the above set of geometric features of bridges together with structural evaluation are used to determine whether a bridge is functionally obsolescence (FO). This measure is explained in detail in the next section. GR and FO primarily evaluate the serviceability of bridges, and are not concerned with bridge safety.

Structurally Deficient (SD) and Functionally Obsolete (FO)

FHWA defines two general forms of deficiencies including Structural Deficiency (SD) and Functional Obsolescence (FO) (6). These two metrics in conjunction with sufficiency rating (will be explained in the next section) are commonly used to determine the eligibility for the allocation of federal bridge replacement funds. Structural deficiency metric uses condition ratings from NBI database as well as structural appraisal ratings. A bridge is called structurally deficient when the condition rating of the bridge is 4 or less for the deck, superstructure, substructure, or culvert and retaining walls, and when the appraisal rating is 2 or less for structural condition or waterway adequacy. On the other hand, functional obsolescence relies only on appraisal ratings. When the appraisal rating is 3 or less for deck geometry, underclearances, or approach roadway alignment, and when the appraisal rating is 3 or less for structural condition or waterway adequacy, the bridge is functionally obsolete. When a bridge is evaluated as both structurally deficient and functionally obsolete, the former will take precedence and the bridge will be classified as structurally deficient (7).

The number of deficient bridges is one of the most commonly cited indicators for the condition of bridges in transportation networks. An overview of the distribution of structurally deficient and functionally obsolete bridges in the nation shows that there are many deficient bridges in the nation (8) which are in need of improvement or repair/rehabilitation actions.

Deficiency Rating (DR)

As the name implies, this metric enables identification of deficient bridges. This measure has been used as a basis to decide on the eligibility and priority of bridges for replacement and rehabilitation (9). In general, DR is defined as a combination of deficiency points assigned to several criteria such as load capacity, bridge condition, bridge width, vertical clearance, and an aggregate minimum level of serviceability. The total deficiency is then calculated as the sum of these deficiency points. Bridge Management Task Group organized by the Pennsylvania DOT (9) suggested an equation for the total deficiency rating (*TDR*) as shown in Equation (B*1*). It includes deficiency points for load capacity (*LCD*), clear deck (*WD*), over clearance (*VCOD*), underclearance (*VCUD*), bridge condition (*BCD*), maintenance life (*RLD*), roadway alignment (*RAD*), and the adequacy of the waterway (*WAD*).

$$TDR = \Phi[LCD + WD + VCOD + VCUD + BCD + RLD + RAD + WAD] \quad \text{(A1)}$$

where Φ is a factor that depends on the functional classification of the highway carried by the bridge. Using this Φ, the total deficiency point does not exceed 100.

As reported by Richardson et al. (10), the deficiency rating algorithm follows the same concept by considering deficiency points for four criteria: load capacity, condition, width, and vertical clearance. The maximum of these deficiency points (or in other words, importance factors) can also be set by state DOTs based on their perceived importance of various aspects of bridge performance. Richardson et al. (10) summarized weights in the original deficiency rating, for the foregoing criteria used by several state DOTs. As shown in Table A1, North Carolina put more weight on load capacity than other states, while Kansas weighted bridge conditions (structural deficiency) more than others in the total deficiency rating.

Table A1- Maximum deficiency points in the original deficiency rating (10)

Criteria	**Maximum deficiency point**				
	North Carolina	**Virginia**	**Nebraska**	**Kansas**	**Alabama**
Load capacity	70	30	50	17	40
Condition	6	46	10	55	40
Width	12	12	12	28	10
Vertical clearance	12	12	28	0	10

DR subjectively evaluates the serviceability and safety performance of bridge systems. If the bridge, in any of the foregoing criteria does not meet the minimum threshold, a deficiency point will be assigned to that bridge. A number of state DOTs such as Alabama, North Carolina, Virginia, Nebraska, and Kansas use bridge deficiency rating to prioritize bridges in need of replacement (10). Deficiency rating was later enhanced by Richardson et al. (10) for the state of Alabama. The maximum weighting factors in the new

Alabama deficiency rating for load capacity, bridge condition, bridge width, and vertical clearance are 40%, 30%, 20%, and 10%, respectively. This new rating addresses the following issues regarding effects of width and vertical clearance in the DR formula, culvert evaluation, and proper load capacity point assignment in the original deficiency rating.

Sufficiency Rating (SR)

Weseman (*6*) proposed Sufficiency Rating (SR) as a measure to be used for allocating funds to bridge programs (11,12). SR ranges from 0% (worst condition) to 100% (best condition), and considers several factors including structural adequacy and safety, functionality and serviceability, essentiality for public use and a term called special reductions to account for issues such as long detour length. Maximum participation of each part is 55%, 30%, 15% and 13%, respectively. If a bridge has an SR rating of 50 or less, it will be eligible for replacement funding. On the other hand, bridges with a sufficiency rating between 50 and 80 are eligible for rehabilitation funds (13). SR can be computed as follows:

$$SR = \sum_{i} S_1^i + \sum_{j} S_2^j + \sum_{k} S_3^k - \sum_{l} S_4^l \tag{A2}$$

where S_1, S_2, S_3, S_4, represent factors related to structural adequacy and safety (e.g. load capacity of the bridge, and NBI condition rating of superstructure, substructure, and culvert), functionality and serviceability (e.g. deck condition and geometry, underclearances, waterway adequacy, approach road alignment, bridge width, and vertical clearances), essentiality for public use (e.g. ADT and detour length), and special reductions, respectively. Details of this metric can be found in (3).

Reliability-based Bridge Inspection (RBI)

National Bridge Inspection Standards (NBIS) mandates biennial thorough inspection of bridges, irrespective of their age and criticality. However, this inspection interval may be insufficient for aging and critical bridges, whereas it can be unnecessary for newly-built bridges. In order to optimize the use of inspection resources while improving the safety of bridges, Washer et al. (14) proposed a set of guidelines for a reliability-based bridge inspection (RBI). The primary objective of RBI is to prioritize the intervals and scope of inspections for bridge components. Application of RBI involves three steps explained as follows:

Step 1: First, the likelihood of failure scenarios is determined. Next, the likelihood of each of these failure modes resulting in structural/serviceability failures within a period of 72 months will be assessed subjectively based on engineering judgment. The estimated likelihood called Occurrence Factor (OF) has four discrete ratings, from 1 (remotely likely) to 4 (high likelihood).

Step 2: In this step, consequences are evaluated. Each failure mode is assigned a Consequence Factor (CF) from 1, indicating minor impact on safety and serviceability, to 4, showing severe consequences as a result of failure, such as structural collapse and loss of life. Expert judgement, and past experience of the consequences of similar components play an important role in understanding the consequences of failure modes. It should be noted that similar failure modes may have different CF in different bridges due to bridge-specific attributes such as ADT, features under and above the bridge, stay-in-place forms, redundancy, composite interaction, and load carrying capacity of the element.

Step 3: In the final step, an index called the Inspection Priority Number (IPN) is calculated. This index is the risk of each failure mode based on the OF and CF ratings explained in **Step 1** and **Step 2**. IPN is determined as follows:

$$IPN_i = OF_i \times CF_i \tag{A3}$$

where OF_i and CF_i are the occurrence and consequence factors of failure mode *i*, respectively. In general, the more the IPN of an element, the shorter the suggested inspection interval for that element, and vice versa. Furthermore, the scope of inspection will be determined based on the identified failure mode and the effectiveness of the inspection technology that will be used to diagnose that damage.

For the calculation of RBI, a reliability assessment panel is recommended by Washer et al. (14) that should consist of bridge inspection experts, bridge management engineers, materials engineers, structural engineers, independent experts, and a facilitator. The outlined procedure for RBI will be conducted by several experts in each group of the panel and their ratings will be averaged to derive the RBI index for the bridge.

Bridge Health Index (BHI)

Bridge Health Index (BHI), first developed by California Department of Transportation (15), takes into account individual bridge elements and combines element-level health index with their weight coefficients to form the overall bridge health condition. BHI is a percentage number ranging from 0 (worse condition) to 100 (best condition) representing the health condition of a bridge (12). BHI can simply be expressed as the ratio of the bridge current value to its initial one (15). The detailed representation of BHI in Pontis and AASHTO BrM is given as follows (12):

$$BHI = \frac{\sum_e H_e Q_e W_e}{\sum_e Q_e W_e} \times 100\% \tag{A4}$$

where Q_e and W_e are the quantity of a bridge element having the health condition H_e and the element weight factor, respectively. W_e is often taken as the failure cost of element *e*. H_e is the element health condition shown in Equation (B5).

$$H_e = \frac{\sum_s k_s q_s}{\sum_s q_s} \times 100\% \tag{A5}$$

In this expression, q_s is the quantity of element *"e"* in state *"s"*, while k_s is the element health index coefficient which is linearly dependent upon its condition-state and is expressed as follows:

$$k_s = \frac{n - s}{n - 1} \tag{A6}$$

with "*n*" equal to the total number of condition-states and *"s"* as the element current condition-state.

BHI is capable of presenting not only the health index of a single element but a bridge system as well. In 2012, 41 states and five municipalities throughout the nation were using Pontis bridge management system (16) that incorporates BHI as a performance metric. BHI has found many applications; at bridge-level the applications include: determining maintenance needs, predicting future bridge conditions, and evaluating lifecycle performance. However, it is less used as an indicator for the level of service. At network-level, BHI is widely used to measure the performance of the network, prioritize projects, predict funding needs, communicate with public and legislature, and allocate resources (11).

Denver Bridge Health Index (DBHI)

As reported by Jiang and Rens (16), there are some issues with the BHI, such as: (a) underestimation of the role of individual element condition-state degradation on the overall bridge health index due to the linear factor k_s and the element weights that are independent of their health condition, and (b) undervaluation of the importance of an individual element condition through consideration of the quantity of elements in the BHI formula. In order to address these issues, Denver BHI (DBHI) was presented by Jiang and Rens (16). DBHI formulation is defined as follows:

$$DBHI = \frac{\sum_e H_e {W_e}^{aj}}{\sum_e {W_e}^{aj}} \times 100\% \tag{A7}$$

where ${W_e}^{aj}$ is the adjusted weight coefficient given as the product of the adjusted element weight factor by an adjustment parameter, *"aj"*. This parameter is defined to be 8 for elements with H_e less than 40%, 1 for elements with H_e greater than 70%, and linearly decreasing from 8 to 1 for elements with $40\% < H_e < 70\%$. Furthermore, the linear model for element health index as a function of condition-state may not conservatively represent the true level of severity of a deteriorated element. To meet the desired expectations, for the city and county of Denver, a nonlinear coefficient ${k_s}^n$ was proposed and applied in the element health index (16):

$$H_e = \frac{\sum_s {k_s}^n q_s}{\sum_s q_s} \times 100\% \tag{A8}$$

The ${k_s}^n$ yields a very low health condition for an element with a severe condition-state.

Integrated Bridge Index (IBI)

Integrated Bridge Index (IBI) was developed by Vanezuela et al. (17) in collaboration with Chilean bridge management experts to aid in prioritization of MR&R decisions for bridge networks in Chile. IBI takes a value between 1 and 10 representing the worst and best conditions, respectively. This metric accounts for a wide series of factors that impact the performance of bridges; factors such as the current condition-state of bridge (*BCI*) and the vulnerability of the bridge to seismic hazards (*SR*), flooding and scour (*HV*), and importance of the bridge in the network (*SI*). After performing a linear regression on results solicited from bridge experts regarding the vulnerabilities and the importance of various factors, IBI formulation was proposed as follows:

$$IBI = -1.411 + 1.299BCI + 0.754HV + 0.458SR - 0.387SI \tag{A9}$$

where *BCI* is the overall condition-state of a bridge, which is derived as:

$$BCI = \frac{\sum_i w_i \times m_i \times ECI_i}{\sum_i w_i \times m_i} \tag{A10}$$

where ECI_i is the condition-state of element *i* determined based on visual inspections (it ranges from 1 (dangerous) to 5 (like-new)), w_i is the factor that indicates the importance of element *i* for stability, security and serviceability of the bridge with values ranging from 1 (least important) to 5 (most important), and m_i is the material factor which represents the vulnerability of the material of element *i* against degradation, deterioration, and other hazards.

IBI tries to reflect the levels of both safety and serviceability of bridges in a community. Due to incorporating network effects in IBI, this index may be used for prioritizing bridges in a network that are in need of MR&R actions.

Vulnerability Rating (VR)

Bridge systems can be exposed to multiple extreme and sudden events during their lifetime, such as flooding, scour, earthquake, collisions, and fatigue. The general approach to account for such hazards is through calculating the likelihood of occurrence and the consequences of such events. Likelihood of hazards depends on the nature of the events, while the consequences of such incidents depend on failure types, functional class of the bridge and the level of public exposure in case of failures. To account for vulnerabilities of bridges against various types of hazards and prioritize the needs, an index called vulnerability rating (*VR*) was developed (18), which ranges from 1 (most severe condition, requiring safety priority actions) to 6 (no hazard affecting the bridge). *VR* is derived for each type of hazard as a function of the vulnerability score (*VS*) given in Equation (B*11*).

$$\begin{cases} VR = 1 & if\ \ VS > 15 \\ VR = 2 & if\ 13 < VS < 16 \\ VR = 3 & if\ 9 < VS < 14 \\ VR = 4 & if\ \ \ \ VS \leq 15 \\ VR = 5 & if\ \ \ \ VS \leq 9 \end{cases} \tag{A11}$$

$$VS = LLS + FTS + TVS + FCS$$

where LLS is the likelihood score, FTS is the failure type score, TVS is the traffic volume score, and FCS is the functional classification score.

Bridge Sustainability Ratio (BSR)

Australia and a number of states in the US including Ohio, North Carolina, Minnesota, and Utah have used Bridge Sustainability Ratio (BSR) to gain long-term perspective on the performance of bridge networks. BSR attempts to capture the nonlinear deterioration rate of bridge components. This rate is often slow at the early ages of bridges, and almost exponentially increases with bridge age. Considering the rate and in general trend of deterioration, appropriate treatment-timing windows can be identified. Performing rehabilitation and preservation actions during these periods can lead to optimal investments and avoid concurrent rapid, nonlinear degradation of components (19).

BSR is defined as the ratio of the budget allocated for maintenance and preservation of bridges over time, by the amount of budget needed to achieve a specific bridge condition target (19). The formulation of BSR is as follows:

$$BSR = \frac{Bridge\ Budget}{Bridge\ Needs} \tag{A12}$$

Based on fiscal analysis, *Bridge Budget* at each year in future can be calculated. However, the more challenging part in Equation (B*12*) is the estimation of *Bridge Needs* through time. Although there does not exist a common procedure to compute these needs, the following set of factors are recommended to be considered in the estimation of the needs (10):

- Detailed long-term decisions for bridge elements in the entire bridge inventory.
- Performance models for condition-states of all bridge elements, including the effect of deterioration.
- Unit costs of applying maintenance, repair, replacement and preventive actions.
- Acceptable levels of condition-states and service for bridge elements, at each year.

For the last feature, different states have different set of criteria. For instance, state of Ohio considers minimum target values for condition-states of four major categories including “general appraisal”, “floor condition”, “wearing surface”, and “paint condition” (19), whereas North Carolina considers a set of target values for deck, superstructure, substructure, culverts, and overhead signs, separately.

Bridge Preservation Index (BPI)

Bridge Preservation Index (BPI) was developed by Caltrans to facilitate bridge preservation decision making (20). The goal of bridge preservation is to promote “actions or strategies that prevent, delay or reduce deterioration of bridges or bridge elements, restore the function of existing bridges, keep bridges in good condition and extend their life” (21). Similar to Bridge Sustainability Ratio, BPI enables identifying appropriate times when preservation actions can be applied (i.e. periodic preservation actions) to further elongate the service life of bridges and reduce the lifetime costs (22). In BPI, preservation actions more focus on bridge elements with good to fair conditions, since for poorer conditions, repair actions might be more effective. BPI uses AASHTO Bridge Element Inspection Manual (23) for the condition-state of the following components (20): deck, steel protective coating, and joint seals. Based on the quantity of elements in each of the condition-states, element level health index is then evaluated using Equation (B5). Following that, BPI is calculated as:

$$BPI = W_D \times DHI + W_P \times PHI + W_J \times JHI \tag{A13}$$

where DHI, PHI, and JHI are the deck, paint, and joint seals health indices, respectively. W_D, W_P, and W_J are the weighting factors that represent the importance of deck, paint and joint seals in the bridge preservation program. Almost similar weights are assigned for deck and paint weighting factors; e.g. in case all the deck, paint and joint components exist in a bridge, weight factors are 0.4, 0.4, and 0.2, respectively.

Using BPI and overall bridge condition, Caltrans set priorities for rehabilitation and preservation actions. If overall bridge condition rating is not high, for all ranges of BPI, rehabilitation actions are needed. In case a bridge is in good condition, preservation actions are recommended with priorities decreasing as BPI increases.

Characteristics of efficient performance measures

One important characteristic of efficient performance measures is that they can identify how successfully a project meets the expected goals. For this purpose, such performance measures should capture all major consequences of actions in candidate projects to help agencies in decision-making (11). In line with recent objectives to preserve serviceability and safety of transportation systems (22), bridge performance measures are expected to assist with long-term bridge management and decision-making. Consequently, performance metrics should be able to capture and reflect short term and long-term effects of improving actions, as well as performance degradations due to continuous traffic movement and environmental stressors.

In general, the consequences of taking Maintenance, Repair and Replacement (MR&R) actions on bridge elements include: agency costs of administration, engineering, and resource mobilization, agency costs of implementing MR&R actions and maintaining traffic, user delay time, impacts on the environment, and increased rate of traffic collisions. On the other hand, if no MR&R action is taken, as a result of deterioration together with continuous traffic loads, condition-state of bridge elements gradually degrades. This increases the vulnerability of bridges to various local damages, and/or partial/complete failures. The occurrence of these failure modes are expedited by extreme events, such as earthquake, flooding, and scour. Adverse direct and indirect consequences are incurred on users and the responsible agencies, if such failure modes occur. Thus, a feature of an efficient performance measure is the ability to integrate the entire spectrum of major consequences for bridge management. In general, the MR&R costs, the likelihood of failure modes and the corresponding consequences vary for bridge types and configurations, and the environment, where the bridge is located. Therefore, a performance measure needs to be applicable for a variety of bridge types and configurations, and environmental conditions.

In order to minimize subjectivity, the consequences may be evaluated objectively through a unified measure such as cost. At the same time, the performance measure should not be too complex to discourage its application in practice. Another feature of a reliable performance measure is the ability to reflect the impact of element-level improvements, as well as defects on the overall performance of the bridge. In other words, a performance measure should be able to combine data at different levels; from element-, to component-, to bridge-levels. These assessments should be based on information that are available to stakeholders. Following the recommendations of the AASHTO guideline in 2010 (23), state DOTs report quantity (percentage) of elements in different condition-states, and thus detailed element-level information is provided to support the foregoing goal.

Finally, since many influencing parameters in the assessment of a bridge performance, such as ADT, user cost, and construction techniques, are subject to change in time, the performance measure should be able to account for such variations.

In the next section, the ability of the studied performance measures to satisfy the objectives presented in this section are discussed.

Discussion of Strengths and Weaknesses of Existing Metrics

The reviewed performance measures have a set of advantages and shortcomings; these are briefly discussed here. In general, the potential cost incurred on users and agencies due to degraded condition-state of bridges can be divided into two categories: the incurred cost because of the reduced level of serviceability and the safety costs due to the loss of structural integrity. Generally, these cost terms increase as the states of bridge elements degrade further. DR, SR, VR, RBI, and IBI are among performance measures that consider these two cost terms as functions of the condition-states of individual elements or groups of components. In particular, DR, SR, and VR provide a more comprehensive and detailed evaluation of the serviceability costs through consideration of the impact of factors such as ADT on the incurred user costs. Structural integrity costs as functions of the condition-state of bridge components are also taken into account in a number of the reviewed metrics. However, the two aforementioned cost terms are not properly combined in many metrics. Combining serviceability and safety costs is performed in DR, SR, and IBI through assigning constant weighting factors for each of the cost terms. These factors represent the contribution of each cost term to the total incurred cost. In some other metrics such as BHI and DBHI, weighting factors are assigned to each element; in this case, factors represent the importance and criticality of corresponding element for the safety and serviceability of the entire bridge. The use of these constant weights may not be appropriate as the contribution of serviceability and safety costs vary based on the condition-state of individual elements, bridge configuration and type, environmental conditions, and service loads, among other factors. Another issue is that safety and serviceability costs are different for various failure modes, and therefore, the weighting factors should vary for different failure scenarios that the bridge may experience. Each failure scenario has its own set of likelihood and consequences. This issue is partially addressed in VR and RBI through the general definition of risk as the combination of the likelihood of the failure and the consequences in terms of safety and serviceability costs. In addition, VR and RBI suggest a platform for the rating of the serviceability and safety consequences based on expert opinion. However, the diverse set of potential consequences of failure modes are divided in these metrics into only four categories. This rough discretization may introduce large errors in the estimation of combined serviceability and safety costs. Another limitation of VR is that its general formulation does not follow the proper definition of risk as the product of the likelihood of events and their corresponding consequences. Instead, the likelihood and consequence factors are added together in VR. Furthermore, each level of extreme event, as potential causes of failure modes, has a particular occurrence likelihood in reality. Thus, the expected vulnerability should account for all such possible scenarios; a feature that is not considered in VR and RBI.

An important characteristic of performance measures is their ability to consider the combined effects of various bridge features and the condition ratings of bridge components. The capability to combine data in multiple levels varies among bridge metrics. For example, BHI and DBHI provide the health condition of an element type in terms of the percentage of individual elements of the same type in various condition-states. These health indices are then combined to derive the bridge-level health condition. For a group of elements such as substructures, superstructures, deck and culverts, NBI rating provides a general appraisal.

In terms of the ability to prioritize bridge preservation actions, BSR directly incorporates deterioration models and fiscal analysis to estimate the required budget to meet a target condition-rating. These processes can provide a basis for preservation actions. This objective is also implicitly incorporated into BPI. However, BSR and BPI are described in general terms, while their application requires various detailed analyses for identification of sources of damage, potential damage modes, and corresponding consequences. Other performance measures are intended to assess the current conditions without looking into the future performance of bridge systems. However, they can be utilized in decision-making frameworks for optimal bridge management and prioritization of preservation actions.

With respect to complexity, a number of metrics such as NBI, GR, SD, and FO are easy to implement and their required data are mostly available. For moderately complex metrics such as DR, SR, VR, IBI and BPI, the performance of bridges are evaluated based on observed condition-states of components from inspections and a set of available formulations and weighting factors. Compared to these metrics, BHI and DBHI require additional efforts for developing weighting factors for different types and categories of elements and for combining these data to evaluate the overall bridge condition. Software programs such as Pontis and AASHTO BrM contain some definitions of BHI which facilitates the application of such metrics. On the other hand for RBI, bridge condition-states must be evaluated in a panel of experts for every single bridge. This approach is impractical when the goal is to assess a large number of bridges.

The ability to reflect effects of variations in parameters such as ADT, user cost, availability of detours, and construction techniques on the performance of bridges partially exists in GR, DR, SR, RBI, BHI, IBI, VR, and BPI through weight factors that are functions of ADT, detour availability, failure cost, or MR&R costs.

It should also be noted that many performance measures such as IBI, Alabama DR, Denver BHI, and BPI are developed to address the particular needs of specific bridge programs considering their bridge features. Since environmental conditions, bridge types and materials, potential hazard events and traffic conditions vary among states, a new set of weighting factors and formulations may be required if these performance measures are intended to be used for other states.

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Appendix B: Calculation of cost terms in OBCI

As mentioned in Section 2, performing MR&R actions on bridge elements incur a number of user and agency costs that are included in OBCI calculations. These costs includes:

- Agency cost of Administration, Engineering and Mobilization (AEM);
- Agency direct cost of performing MR&R actions (MR&R);
- Agency cost of Maintenance of Traffic (MOT); and
- User cost incurred from Delay time, Vehicle operation, and Excess emission (DVE).

For AASHTO CoRe elements (1), a number of state Department of Transportations (DOTs) have determined element-level MR&R costs. Other required information are existing condition-states that are suitable for the application of considered actions as well as the likely condition-state of the element after performing such improving actions. These condition-states are often provided in a 1 to 5 condition-rating system. Some of the states that have collected these information are Colorado (2), Michigan (3), Delaware (2), Minnesota (4), Louisiana (2), and Florida (5). Recently, AASHTO has recommended state DOTs to provide element-level inspections on a condition-state rating system of 1 to 4 (*19-20*). The definition of condition-states in this rating system is different from that in the 1 to 5 condition-rating system, for which element-level costs are vastly available. Thus, in line with AASHTO's new condition-rating system, MR&R costs should be converted to those based on the condition-state rating system of 1 to 4. For this purpose, this section proposes a simple and practical mapping system that is based on the definitions of condition-states. Furthermore, specific adjustments are recommended to realistically calculate project-level MR&R costs from element-level ones; a feature that is missing in many existing frameworks and measures. A systematic framework is proposed for calculation of the MOT cost, which relies on logical considerations and the unit costs reported by Ohio DOT (ODOT) for crew, equipment and police enforcement. A formulation is also proposed for the AEM cost, which uses the overhead factor provided by state DOTs based on their cost histories. Moreover, an analytical step-wise procedure is developed here for the calculation of the expected DVE cost for MR&R work plans of any scale and duration without requiring detailed hourly traffic analyses.

In the next sections, the above cost terms are elaborated and discussed. These costs are then computed for a set of projects on three bridges in Ohio. It is noteworthy that the following procedures are also published in (6).

B.1. Cost terms and their analysis procedures

This section introduces the calculation procedures for agency and user cost terms in OBCI, at element-, component-, bridge-, and network-levels.

B.1.1 Agency cost - Maintenance, Repair, and Replacement (MR&R) costs

B.1.1.1 Element-level MR&R costs

In general, MR&R cost of an element depends on the material and type of the element, current condition-state of portions of the element that are planned to be repaired, and their target condition-state. As mentioned in the previous section, in many research studies by state DOTs and other researchers, such element-level MR&R costs are presented (e.g. (2–5)). However, the current condition-state corresponding to these costs are based on a 1-to-5 condition-state rating system, which should be converted to those based on the new 1-to-4 AASHTO recommended rating system. This task can be accomplished through the application of the conversion tables presented in AASHTO (7). Due to the complexities involved in this process, authors also suggest a simple and practical mapping procedure that is based on the general definitions of condition-states and feasible actions that are suggested for these condition-states.

In this procedure, one needs to first identify the material and type of the element. For elements out of concrete or steel, the following conversion is proposed: condition-states 1, 4, and 5 of the old system are equivalent to condition-states 1, 3, and 4 in the new rating system, and condition-states 2 and 3 of the old system are equivalent to condition-state 2 in the new rating system. It is worthy to note that at least for steel elements, the considered rule is identical to AASHTO (7). An issue in this mapping process is the fact that in some cases, there are two different cost values for one action in the 1-to-5 rating system; one starting from condition-state 2, the other starting from condition-state 3. In these cases, the cost should be averaged and stored as the cost of that action when prior condition-state in the new 1-to-4 rating system is 2.

For other elements, such as embankments, bearing devices and drainage systems, the definitions of the 1-to-5 and 1-to-4 rating systems are compared and the equivalent current condition in the new 1-to-4 rating system is identified. For instance, the repair costs of the drainage system that are reported in (2) for state of Florida are used for MR&R cost calculation of the sample bridges in this article. For this element, cost values for repair actions are provided for four current condition-states “Excellent”, “Minor deterioration”, “Moderate deterioration”, and “Major deterioration”. According to ODOT inspection manual (8), condition-states 1 to 4 for a drainage system are defined as “Excellent” with no clog, “Satisfactory” with “minor deficiency to drainage system”, “Poor” with “advanced deterioration”, and “Critical” with “major deterioration”. Thus, there is a one-to-one mapping between the prior condition-states “Excellent”, “Minor deterioration”, “Moderate deterioration”, and “Major deterioration”, and the new 1-to-4 AASHTO rating system.

Furthermore, in order to identify condition-state improvements resulting from taking MR&R actions on elements, the following rules are established:

- Replacing any element improves the condition of that element to condition-state 1.
- For elements that are made from concrete or steel material, all other MR&R actions such as repairing and major rehabilitation, improve the condition-state to 2 (9).
- For elements made from materials other than steel or concrete, the definitions of condition-states 1 to 4 together with the description of the MR&R action that is applied to the element can be used to determine the condition-state improvements. In these cases, in addition to replacing the unit, a major rehabilitation may also improve the element to condition-state 1. For instance, “having no clog” is defined as condition-state 1 for a drainage system. When the drainage system is in condition-state 2, and one performs flushing, debris are expected to be removed and thus the condition-state of that drainage element will be 1.

Based on the above rules, all actions improve the elements to condition-state 1 or 2. This is also identical to the default assumption in AASHTO BrM bridge management software (10).

Due to differences between the unit quantity of some elements in the new inspection reports based on the AASHTO rating system and the cost units that are available for MR&R actions for those elements, realistic assumptions for the physical characteristics of those elements may be required for the estimation of MR&R costs. For instance, MR&R costs of pier columns/bents are available in terms of linear foot, whereas the unit quantity of columns in the inspection reports is “each”. Considering a realistic value for the width of columns, e.g. two and a half feet, MR&R costs of pier columns in the unit of “each” can be estimated.

In addition, if MR&R costs particular to state B are employed for state A, the following procedure should be used to adjust the costs:

$$Cost\ in\ state\ A = \frac{Adjustment\ factor\ for\ the\ state\ A}{Adjustment\ factor\ for\ state\ B} \times Cost\ in\ state\ B \tag{B1}$$

where state adjustment factors are provided by US Army Corps of Engineers (11). Notably, since the utilized cost values are reported in previous years, e.g. year *n*, net present value of each cost term should be calculated, given by:

$$Cost\ in\ previous\ year = \frac{Annual\ average\ CPI\ for\ previous\ year}{Annual\ average\ CPI\ for\ year\ n} \times Cost\ in\ year\ n \tag{B2}$$

$$Cost\ in\ current\ year = (1.03) \times Cost\ in\ previous\ year \tag{B3}$$

where CPI is the Consumer Price Index given in Table 24 of the Consumer Price Index Detailed Reports (12). In addition, 3% is considered as the rate of increase for costs from previous to current year.

B.1.1.2 Project-level MR&R costs

A project-level MR&R work plan may be at component- (i.e. approach, deck, superstructure, substructure, culvert, channel, or signs/utilities), bridge-, or network-level (i.e. a portfolio of bridges). At the component-level, due to the availability of crew and materials for repair actions of constituent elements, the costs associated with mobilization of crew and materials per element are less than that if only one element was to be repaired. A reduction factor, α_C, is considered here to account for these effects in the computation of MR&R costs. With the same analogy, a reduction factor, α_B, is considered for the calculation of bridge-level MR&R costs from component-level costs. Consequently, component-, and bridge-level MR&R costs can be calculated as:

$$MR\&R^C = \alpha_C \times \sum_{e=1}^{M_C} MR\&R_e^C \tag{B4}$$

$$MR\&R^B = \alpha_B \times \sum_{c=1}^{M_B} MR\&R_c^B \tag{B5}$$

where $MR\&R_e^C$ and $MR\&R_c^B$ are the MR&R cost of element *e* in component *C*, and MR&R cost of component *c* in bridge *B*, respectively. The terms M_c and M_B stand for the total number of the elements in component *C* and the total number of components in bridge *B*, respectively. Agencies can calibrate these reduction factors α_C and α_B based on their cost histories. In this study, α_C and α_B for all components and bridges are taken as 0.8 and 0.9, respectively. It is also worthy to note that some state DOTs such as Caltrans (13) have provided cost ranges for unit construction cost per deck area of various types of bridges based on their cost histories. These values can be adopted for the calculation of the replacement cost of bridges, which is a substitute for calculating the cost of bridge replacement according to Equation (B5).

For network-level MR&R cost calculation, reduction factors can be disregarded, since bridges are mostly apart and thus the MR&R actions on each bridge is performed independently with new laborers and equipment.

B.1.2 Agency Cost - Maintenance of Traffic (MOT) costs

To assure safety of workers and drivers, and direct traffic smoothly alongside a bridge repair site, agencies protect the working area by the help of crew and equipment, and if necessary utilizing police enforcement. According to ODOT Office of Estimation in 2016, “three laborers, one arrow board, one truck with attenuator, and one truck/flatbed for barrel placement and removal” to maintain the traffic cost \$260/hour on average (14,15). Law enforcement cost is also estimated as \$65/hour. In order to systematically calculate MOT cost of a repair work plan with any duration, the following logical assumptions are considered.

- Following the discussion with personnel from ODOT office of estimating and road department, the average number of hours that bridge laborers work is 8 hours/day.
- On weekends no worker is present, and therefore the cost of MOT over that period is reduced to the equipment that direct the traffic. As an estimation, the $260/hour unit cost for "three laborers, one arrow board, one truck with attenuator, and one truck/flatbed for barrel placement and removal" is reduced by 60% for weekends.
- The $65/hour cost of law enforcement is not considered for weekends.
- Police enforcement is assumed to be present at working sites, where more than 40% of the road on bridge is closed.

Thus, for an MR&R project at level *l* (element-, component-, bridge-level), MOT cost is calculated as:

$$\begin{aligned} MOT^{l} &= (8 \times T^{l} \times \$260 + 8 \times T^{l} \times F^{N_{Cl}} \times \$65 + 16 \times T^{l} \times 0.4 \times \$260) \\ &\quad + \left(2 \times \left\lfloor \frac{T^{l}}{7} \right\rfloor \times 24 \times 0.4 \times \$260\right) \end{aligned} \tag{B6}$$

where T^{l} is the duration of performing the repair work plan, which is at level l. The term $F^{N_{Cl}}$ is a factor taking a value of 1 or 0, indicating the presence/non-presence of police officers. Identifying the number of closed lanes, N_{Cl}, depends on many factors. Without a need for detailed hourly traffic analyses, a method is proposed to assist agencies with optimal decision on the number of closed lanes based on average daily traffic. This also results in more accurate calculation of the MOT cost. Given that the user cost of DVE depends on T^{l} and N_{Cl}, step-wise algorithms for objective estimation of these two parameters are presented later in the paper, where calculation procedures for DVE costs are elaborated.

B.1.3 Agency Cost - Administration, Engineering and Mobilization (AEM) costs

AEM costs associated with an MR&R project at level l (element-, component-, bridge-level) can be estimated by:

$$AEM^{l} = \beta \times (MOT^{l} + MR\&R^{l}) \tag{B7}$$

where β is the overhead factor. ODOT structure team suggests 0.25 for this factor. In general, this factor depends on the scale, type and configuration of bridges, among others, and state DOTs may calibrate this factor based on their cost histories.

B.1.4 User Cost - Delay Time, Vehicle Operation, and Excess Emission (DVE) costs

In performing MR&R actions on members of a bridge, the bridge may be partially or completely closed. This affects the traffic that passes the bridge, since car and truck drivers need to either reduce their speed or decide to drive through detours if available. For each project at level l, DVE cost is calculated using:

$$DVE^{l} = T^{l} \times (t_{ij}^{D/R} - t_{ij}^{O}) \times [(ADT - ADTT) \times \rho_{C} + ADTT \times \rho_{T}] \tag{B8}$$

where t_{ij}^{O} is the average original time that is spent by drivers to drive from point *i* to point *j* when no repair actions are performed on the bridge, whereas $t_{ij}^{D/R}$ is the average time to drive from point *i* to point *j* when repair projects are conducted on the bridge. Therefore, $(t_{ij}^{D/R} - t_{ij}^{O})$ is the extra time spent by users due to speed reduction and/or traffic rerouting because of repair actions on the bridge. Finally, ρ_{C} and ρ_{T} are the unit user costs for cars and trucks due to delay time, vehicle operation, and excess gas emission, respectively. These values can be found in (16,17). Following Bocchini and Frangopol (18), t_{ij}^{O} can be computed by:

$$t_{ij}^{O} = t_{ij}^{F} \times \left[1 + \alpha(\frac{f_{ij}}{f_{ij}^{c}})^{\beta}\right] \tag{B9}$$

In this equation, t_{ij}^{F} is the time required to cover path *ij* at free flow speed, which passes through the bridge. This can be estimated by the path length and the original speed limit of the path. The term f_{ij} represents the ADT on the highway segment *ij*. The term f_{ij}^{c} stands for the critical flow (maximum flow capacity) of the bridge, and α and β are also parameters considered as 0.15 and 4, respectively (used in (18)). Moreover, in Equation (B*9*), $t_{ij}^{D/R}$ is calculated according to the formulation presented by Bocchini and Frangopol (18) as follows:

$$t_{ij}^{D/R} = t_{ij}^{R} \times \left[1 + \alpha(\frac{f_{ij}}{f_{ij}^{c}})^{\beta}\right] + \sum_{b \epsilon ij} s_{b,ij} \times t_{b,ij}^{d} \times \left[1 + \alpha(\frac{s_{b,ij} . f_{ij}}{f_{b,ij}^{c}})^{\beta}\right] \tag{B10}$$

where t_{ij}^{R} is the free flow time for drivers to travel from point *i* to point *j* through the bridge which is affected by a repair project. In this case, the speed limit on the bridge is usually reduced compared to its original value, depending on the original speed limit, the protection required for the work zone, and whether workers are present in the work zone (19). The term $f_{b,ij}^{c}$ stands for the critical flow (maximum flow capacity) of detour *b* joining points *i* and *j*. In addition, $t_{b,ij}^{d}$ is the time required to pass from point *i* to *j* through detour *b* at free flow speed. Finally, $s_{b,ij}$ is the fraction of traffic from point *i* to *j* that passes through detour *b*, which on a logical basis can be considered as the ratio of the closed lanes on the bridge to the total number of lanes on that bridge. In this research, an optimization procedure is developed to identify this factor, by finding the scenario for the number of closed lanes that minimizes the incurred costs of MOT and DVE for the duration of the repair project. The flowcharts for identifying the optimal number of closed lanes together with the calculation of the associated MOT and DVE costs for repair and bridge replacement work plans are presented in Figure B1 and Figure B2, respectively. As can be seen, estimation of the MOT and DVE costs depends on the duration of the repair/bridge replacement work plan. Correct identification of this parameter is important to arrive at accurate cost calculations. Thus, this study proposes analytical formulations for the estimation of the required time for conducting MR&R work plans.

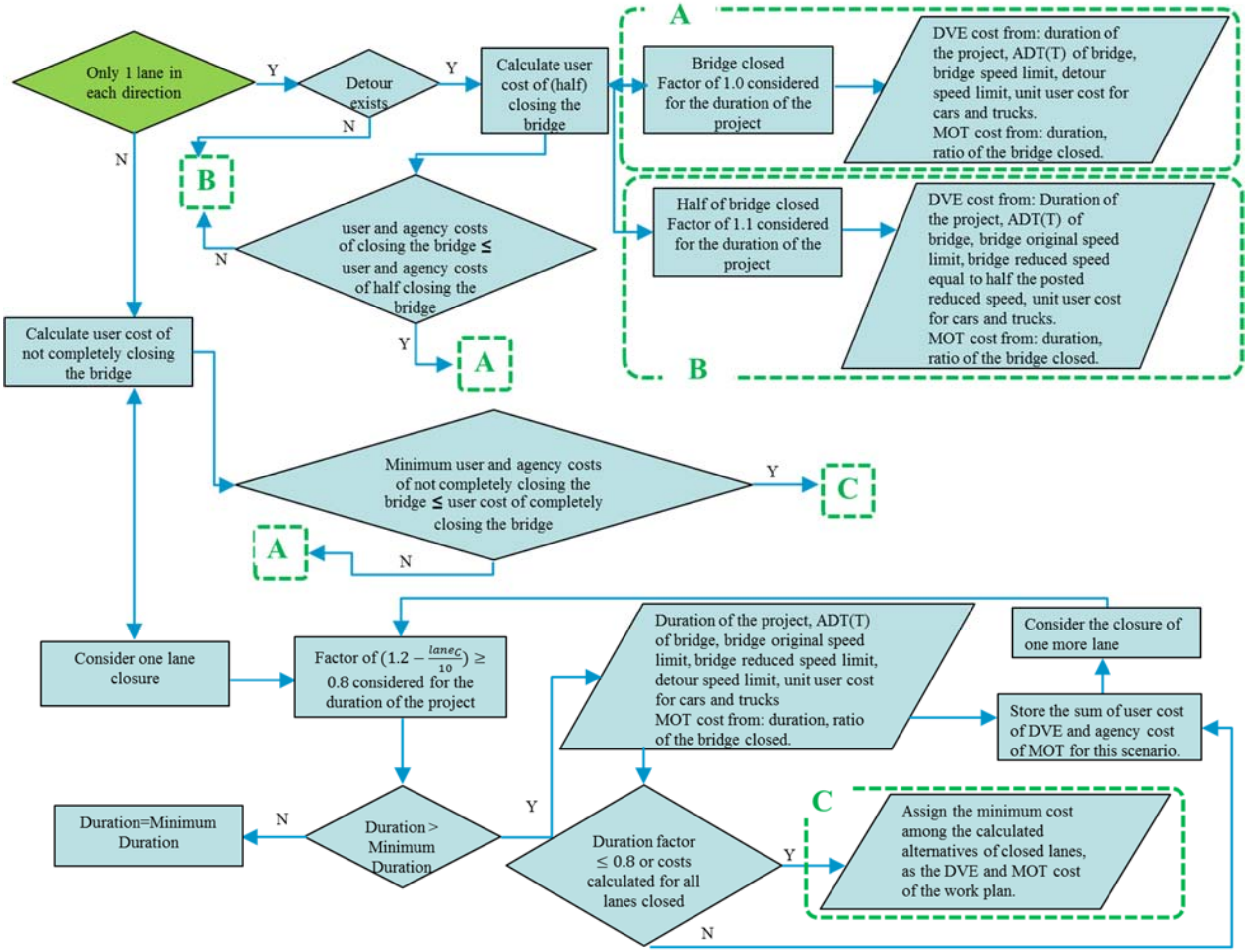

Figure B1- The flowchart for identifying the optimal number of closed lanes, together with the calculation of the associated MOT and DVE costs for a repair work plan.

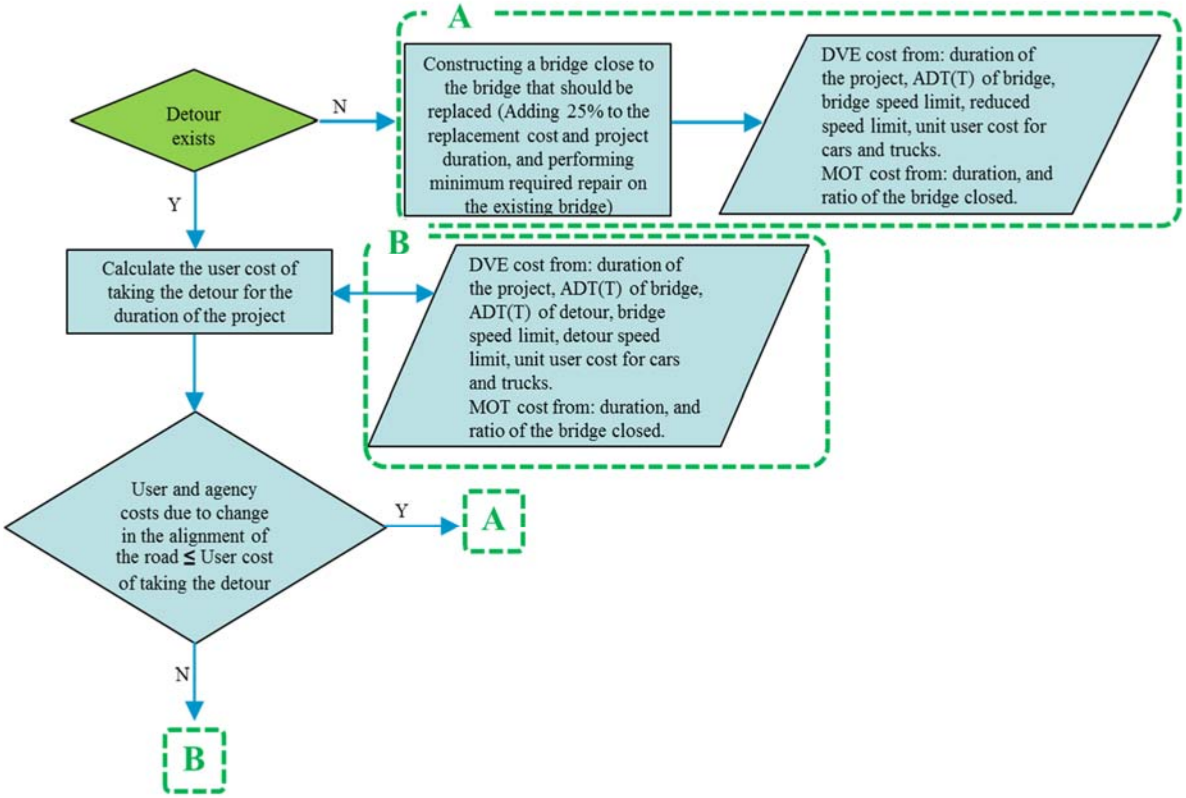

Figure B2- The flowchart for identifying the optimal number of closed lanes, together with the calculation of the associated MOT and DVE costs for a bridge replacement work plan.

B.1.4.1 Element-Level Duration of MR&R Actions

At element-level, formulas are developed that calculate the durations as a function of the quantity of elements receiving MR&R actions, and the type of actions, i.e. repair or replacement, as follows:

- For elements, for which MR&R costs are calculated based on the unit of "each", such as bearing devices, durations of MR&R actions, T^E, are calculated as follows:

  $$T^E = RF_E \times (N_E \times t_E^T) \qquad \text{(B11)}$$

  where N_E is the number of element *E* receiving an MR&R action of type *T*, e.g. 15 bearing devices receiving repair, t_E^T is the required duration of performing the MR&R action of type *T* on one element, and RF_E is the reduction factor particular to element *E*. The latter accounts for the reduced time of the MR&R action on element *E* when more than one of that element receives MR&R actions. This is because of the reduced time required for mobilization of crew and materials. This term, RF_E, is an inverse function of the number of elements improved by the MR&R action. As an example, authors suggest $\frac{1}{\left(1+\frac{N_E}{100}\times 3\right)} \geq \frac{1}{4}$ as the reduction factor for the bearing device element, and $1\,\frac{day}{each}$ for the repair action on this element.

- For other elements, T^E is calculated as:

  $$T^E = c \times (a^E + b^E \times Q^E) \qquad Q^E > 0 \qquad \text{(B12)}$$

  where a^E and b^E are constant values, which are particular to element *E*, c is a factor indicating the type of MR&R action; 0.75 for repair and 1.00 for replacement action, and Q^E is the quantity of element *E*. For instance, for floor/slab element, authors suggest 1.05 and 0.005 for a^E and b^E, respectively.

It is worthy to note that the existing factors in Equations (B*11*) and (B*12*) should be adjusted based on agencies' information on the duration of MR&R activities and/or engineering elicitation. Furthermore, since the calculated element-level durations are the required *working days* to perform MR&R actions, the total duration of a work plan, including weekdays and weekends, is equal to $T^E + 2 \times \left\lfloor \frac{T^E}{7} \right\rfloor$, with $\lfloor \quad \rfloor$ as the floor of the ratio $\frac{T^E}{7}$, which determines the minimum number of weekends that the project faces. The same statement is true for project-level duration of MR&R work plans, which is explained in the next section.

B.1.4.2 Project-Level Duration of MR&R Actions

Component- and bridge-level work plan durations, i.e. T^C and T^B, can be estimated through reduction factors ω^C and ω^B, applied to the sum of the required working days for the constituent elements/components. In mathematical terms:

$$T^C = \omega^C \times \sum_{k=1}^{M_C} T_C^e \qquad \text{(B13)}$$

$$T^B = \omega^B \times \sum_{c=1}^{M_B} T_B^c \qquad \text{(B14)}$$

where T_C^e and T_B^c are the required time for performing MR&R action(s) on element *e* of component *C*, and on component *c* of bridge *B*, respectively.

The foregoing reductions in the project-level MR&R work plans are due to the less required time for the mobilization of crew and material for MR&R actions on constituent members. Based on engineering judgment, authors suggest 0.9 and 0.75 for ω^B and ω^C, respectively. However, for the replacement of bridges, due to the availability of large spaces for the work plan due to complete closure of the bridge, ω^B is suggested as 0.8. State DOTs and other entities may conduct more objective evaluations to determine these factors.

B.2. Cost calculation of case study bridges

This section demonstrates the application of the proposed cost calculation procedures for three bridges in Ohio. These three bridges are selected by ODOT and their specification are presented in Table B1. All of them have the same ratings of general appraisal of 7. Bridge # 2590271 has a unique feature with no detour and low average daily traffic, while Bridge # 2504316 and 2504316 have heavy traffic.

Table B1- Specifications of the three sample bridges

Structure File No.	Inventory Bridge No.	Bridge Type	Year Built	No. of Spans	No. of lanes	Length (FT)	Average Daily Traffic	Detour length (Mile)	General Appraisal
2513927	I.R. 270 over CSX RR & private RD	Steel/Beam/ Continuous	1968	3	3	178.0	135,746	1	7
2590271	Drive way over Dry run	Prestressed concrete/Box beam/Continuous	1992	3	2	110.0	50	99	7
2504316	I 70 over Hague Ave	Steel/Beam/ Continuous	1973	2	8	113.8	143,747	1	7

Following AASHTO (7) and ODOT (8), bridge elements are categorized into three groups including National Bridge Elements (NBE), Bridge Management Elements (BME), Agency Developed Elements (ADE). In a collaborative effort with ODOT, Fereshtehnejad et al. (14,15) established minimum structural/operational thresholds for the condition-state of these elements, as well as for the defects associated with specific bridge elements (8). The condition-rating system follows the most recent rating system suggested by AASHTO (7,9), which ranges from 1 (good), to 4 (severe). On this basis, an NBE, primary ADE, or defect flag with more than 2% in condition-state 3 or any quantity in condition-state 4, or a BME or non-primary ADE with more than 10% in condition-state 3 and 4, is considered structurally/operationally unsafe. In this case, repair actions should be performed on the quantities in condition-state 3 and 4 to improve them to at least condition-state 2. This level of effort for repair actions is considered as “minimum repair” in this paper. Moreover, Fereshtehnejad et al. (14,15) suggested another extent for repair actions that improves the condition of a bridge member to its like-new state. For this goal, the quantities of constituent elements of a member in condition-state 3 or 4 should be repaired to improve to at least condition-state 2, and those quantities in condition-state 2 should be maintained to stay in condition-state 2. This type of repair is referred to as “like-new repair” in this article. Based on the cost formulations and considerations in previous sections, the agency-required budget for the minimum and like-new repair actions for the three sample bridges are estimated as $667,540 and $814,441 for Bridge #2513927, $138,313 and $271,918 for Bridge #2590271, and $20,691 and $527,945 for Bridge #2504316. Notably, these costs do not exceed the agency cost incurred by the replacement of the entire bridge.

Detailed budget information for MR&R actions of each bridge are given in Tables B2~B4. The required budget for minimum repairs on Bridge #2513927 exceeds $667k since a great portion of elements on this bridge require moderate to extensive repairs. For example:

- 1400 ft^2 of the approach wearing surface in condition-state 3 need moderate repair,
- 14 bearings in condition-state 3 and 4 need either extensive repair or replacement,
- 12 diaphragms that have severe deficiencies and are reported in condition-state 4 should be replaced,
- Entire 112 ft of backwalls in condition-state 4 should receive extensive repair. The latter contributes the most to the MR&R cost of the bridge.

Furthermore, this project requires 21 days, incurring about $73,000 for the MOT cost and $134,000 for AEM cost. The same analysis is conducted for Bridge #2590271 for the minimum required actions, and for Bridge #2504316 for the project that improves all elements to their like-new state. As expected, the MOT cost of Bridge #2504316 is as high as MR&R cost since the required time for conducting like-new repairs on this bridge is significant, i.e. 66 days. Moreover, the DVE costs of Bridge #2590271 and Bridge #2504316 are estimated as high as the total agency costs due to the heavy traffic that passes these bridges.

As a verification for the calculated costs, ODOT engineers independently calculated the agency cost of performing minimum repairs for Bridge #2513927, based on their preliminary bridge work estimates and their engineering judgement. They estimated the cost as $618,902, which is 7% less than the calculated cost using the proposed procedure (Table B2).

It should be also mentioned that the accuracy of the cost estimates considerably relies on the accuracy of the input element-level costs and parameters in cost-calculation formulas. Thus to enhance the accuracy of cost estimates, agencies and state DOTs may determine those element-level costs and parameters based on their bid histories.

Table B2- Disaggregating the required budget for minimum repairs on Bridge #2513927

Component	**Description**	**Element MR&R Cost ($)**	**Total Agency cost ($)**	**Bridge MR&R cost ($)**	**Bridge AEM cost ($)**	**Bridge MOT cost ($)**	**Bridge DVE cost ($)**	**Duration (Days)**
Approach	Repair 1400 ft^2 of the approach slab in condition-state 3	146,564	667,546	454,730	133,510	79,306	297,146	21
Deck	-	-						
Super-structure	Repair 28 ft of the girder in condition-state 3	5,125						
	Replace 12 Diaphragm/X-Frames in condition-state 4	94,695						
	Repair seven bearing devices in condition-state 3 and replace seven bearing devices in condition-state 4	58,834						
Substructure	Extensive repair the 112 ft of backwalls in condition-state 4	231,760						

Table B3- Disaggregating the required budget for minimum repairs on Bridge #2590271

Component	**Description**	**Element MR&R Cost ($)**	**Total Agency cost ($)**	**Bridge MR&R cost ($)**	**Bridge AEM cost ($)**	**Bridge MOT cost ($)**	**Bridge DVE cost ($)**	**Duration (Days)**
Approach	Repair 258.5 ft^2 of the approach slab in condition-state 3 and 4	28,200	138,313	70,015	27,663	40,636	9,080	10
	Repair entire embankments in condition-state 4	1,860						
Deck	Repair 690 ft^2 of the wearing surface in condition-state 3 and 4	49,594						
	Repair the 10 ft of railings in condition-state 3	1,377						
	Repair the existing two drainage system in condition-state 3	685						
	Repair the 40 ft of expansion joint in condition-state 3	1,000						
Superstructure	**-**	-						
Substructure	**-**	-						
Channel	**-**	-						
Sign	**-**	-						

Table B4- Disaggregating the required budget for like-new repairs on Bridge #2504316

Component	**Description**	**Element MR&R Cost ($)**	**Total Agency cost ($)**	**Bridge MR&R cost ($)**	**Bridge AEM cost ($)**	**Bridge MOT cost ($)**	**Bridge DVE cost ($)**	**Duration (Days)**
Approach	Maintain 8520 ft^2 of the approach wearing surface in condition-state 2, e.g. sealing or patching	182,570	527,945	221,280	105,590	201,080	695,438	66
	Maintain 100 ft^2 of the slab in condition-state 2	2,500						
Deck	Maintain 120 ft^2 of the floor/slab in condition-state 2	3,000						
	Maintain 3 ft^2 of the edge of floor/slab in condition-state 2	75						
	Maintain 200 ft^2 of the deck wearing surface in condition-state 2	4,286						
	maintain 2 ft of the railing system in condition-state 2	78						
	Repair the 95 ft of expansion joint in condition-state 3, and maintain the 300 ft rest of the expansion joint in condition-state 2	2,375						
Super-structure	Maintain 54 bearing devices in condition-state 2, e.g. cleaning, paiting and greasing or rehabilitating them	4,655						
	Maintaining the 2050 ft of the protective system in condition-state 2	40,307						
Substructure	Maintaining the 40 ft of the abutment walls in condition-state 2	5,791						
	Repairing the 5 ft of defected pier cap in condition-state 3	4,423						
	Repairing 2 ft of backwalls in condition-state 4, and maintaining the 20 ft of backwalls that are in condition-state 2	8,700						
Sign	-	-						

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Appendix C: Details of optimal MR&R actions for NHS bridges of district 3

The developed computer code for the optimal allocation of budget is utilized for the assignment of optimal MR&R work plan for the 484 NHS bridges in district 3, using element-level inspection data collected in 2017. The considered maximum budget is $14,344,280.

C.1. Suggested MR&R actions for NHS bridges in district 3, following the developed optimal budget allocation algorithm

The optimization algorithm determined 109 bridges to receive MR&R actions, with the total agency cost of $14,342,844. The details of the optimal MR&R actions for these bridges are presented in Table C-1. In these results, all NHS bridges in district 3 that are selected to receive MR&R actions, as well as the description of the MR&R actions on their elements, the agency cost for performing these MR&R actions, and an estimation for the duration of the MR&R actions are shown.

Table C.1- The suggested MR&R actions for NHS bridges in district 3, following the developed optimal budget allocation algorithm

Bridge SFN	County-Route-SLM	Optimal Actions	Agency Cost on District (MR&R+AEM+MOT)	Estimated Project Duration (Days)
'7001118'	'RIC-00030-10738'	‘Reinforced Concrete Deck(2), Strip Seal Expansion Joint(2), Metal Bridge Railing(2), Wearing Surfaces(2), Girder/Beam Steel(1), Moveable Bearing (Roller/Sliding)(1), Steel Protective Coating(1), Columns Reinforced Concrete(1), Abutment Reinforced Concrete(1),'	'$2349K'	159
'2202344'	'ERI-00006-28834'	‘Truss Steel(1), Gusset Plate Steel(1), Moveable Bearing (Roller/Sliding)(1), Replace Deck Items, Abutment Reinforced Concrete(2)’	'$1706K'	68
'4701496'	'LOR-00010-05049'	'Steel Protective Coating(1), '	'$1250K'	114
'5200660'	'MED-00018-06849'	'Replace Deck Items, Girder/Beam Steel(1), Steel Protective Coating(1), Columns Reinforced Concrete(1), '	'$907K'	31
'8500215'	'WAY-00003-11628'	'Wearing Surfaces(1), Steel Protective Coating(1), '	'$738K'	101
'5203813'	'MED-00071-19916'	'Steel Protective Coating(1), '	'$502K'	75
'5203848'	'MED-00071-19916'	'Steel Protective Coating(1), '	'$502K'	75

'3902048'	'HUR-00061-18556'	'Replace Deck Items, Abutment Masonry(1), '	'$465K'	15
'7000243'	'RIC-00013-05319'	'Truss Steel(1), Floorbeam Steel(1), Gusset Plate Steel(1), Steel Protective Coating(1), '	'$309K'	41
'8502854'	'WAY-00057-12777'	'Moveable Bearing (Roller/Sliding)(1), Steel Protective Coating(1), '	'$254K'	37
'8502374'	'WAY-00030-21345'	'Girder/Beam Steel(1), Steel Protective Coating(1), Abutment Reinforced Concrete(1), '	'$236K'	33
'0304891'	'ASD-00250-17896'	'Steel Protective Coating(1), '	'$218K'	32
'7001657'	'RIC-00030-19186'	'Girder/Beam Steel(1), Steel Protective Coating(1), '	'$212K'	29
'7001681'	'RIC-00030-19186'	'Girder/Beam Steel(1), Steel Protective Coating(1), '	'$212K'	29
'4704924'	'LOR-00090-17846'	'Girder/Beam Steel(1), Moveable Bearing (Roller/Sliding)(1), Steel Protective Coating(1), '	'$203K'	20
'4704894'	'LOR-00090-17846'	'Girder/Beam Steel(1), Moveable Bearing (Roller/Sliding)(1), Steel Protective Coating(1), '	'$192K'	19
'0304956'	'ASD-00250-18186'	'Steel Protective Coating(1), '	'$178K'	27
'5201802'	'MED-00057-01370'	'Reinforced Concrete Slab(1), Columns Reinforced Concrete(1), Abutment Reinforced Concrete(1), Wearing Surfaces(1), '	'$162K'	7
'4704398'	'LOR-00090-11567'	'Reinforced Concrete Deck(2), '	'$150K'	25
'5201861'	'MED-00057-02650'	‘Strip Seal Expansion Joint(1), Wearing Surfaces(1), Girder/Beam Steel(1), Moveable Bearing (Roller/Sliding)(1), Steel Protective Coating(1)’	'$132K'	10
'7004478'	'RIC-00071-15277'	'Steel Protective Coating(1), '	'$128K'	20

'8500339'	'WAY-00003-12017'	'Reinforced Concrete Slab(1), Columns Reinforced Concrete(1), Wearing Surfaces(1), '	'$119K'	7
'1701851'	'CRA-00030-20756'	'Girder/Beam Steel(1), Steel Protective Coating(1), '	'$115K'	13
'7004508'	'RIC-00071-15277'	'Steel Protective Coating(1), '	'$109K'	15
'4701089'	'LOR-00020-13557'	'Reinforced Concrete Slab(1), Abutment Reinforced Concrete(1), Reinforced Concrete Bridge Railing(1), '	'$107K'	5
'1701207'	'CRA-00030-06908'	'Wearing Surfaces(1), '	'$102K'	4
'4703510'	'LOR-00058-24905'	'Reinforced Concrete Slab(1), Abutment Reinforced Concrete(1), Reinforced Concrete Bridge Railing(2), '	'$97K'	6
'3900754'	'HUR-00020-08128'	'Girder/Beam Steel(1), Steel Protective Coating(1), '	'$85K'	9
'1701878'	'CRA-00030-20756'	'Girder/Beam Steel(1), Steel Protective Coating(1), '	'$83K'	10
'4729692'	'LOR-0080K-16366'	'Culvert Reinforced Concrete(1), '	'$76K'	1
'5200636'	'MED-00018-06569'	'Reinforced Concrete Slab(1), Columns Reinforced Concrete(1), Abutment Reinforced Concrete(1), Wearing Surfaces(1), '	'$76K'	6
'7003587'	'RIC-00071-04389'	'Steel Protective Coating(1), '	'$71K'	11
'7003595'	'RIC-00071-04389'	'Steel Protective Coating(1), '	'$71K'	11
'5203066'	'MED-00071-08598'	'Steel Protective Coating(1), '	'$70K'	11
'8504725'	'WAY-00250-05049'	'Reinforced Concrete Slab(1), '	'$70K'	2
'8502439'	'WAY-00030-26085'	'Culvert Reinforced Concrete(1), '	'$69K'	1
'3960358'	'HUR-CLEVE-00040'	'Reinforced Concrete Slab(1), Wearing Surfaces(1), '	'$66K'	4
'4707613'	'LOR-00480-02029'	'Columns Reinforced Concrete(1), Abutment Reinforced Concrete(1), '	'$62K'	4

'1701924'	'CRA-00061-03609'	'Girder/Beam Steel(1), Moveable Bearing (Roller/Sliding)(1), Abutment Reinforced Concrete(1), '	'$61K'	3
'2202018'	'ERI-00006-18016'	'Wearing Surfaces(1), Columns Reinforced Concrete(1), '	'$61K'	3
'3901505'	'HUR-00020-25615'	'Columns Reinforced Concrete(1), '	'$57K'	6
'5201837'	'MED-00057-02159'	'Reinforced Concrete Slab(1), Abutment Reinforced Concrete(1), Wearing Surfaces(1), '	'$56K'	4
'4701119'	'LOR-00020-13557'	'Reinforced Concrete Slab(1), Abutment Reinforced Concrete(1), '	'$54K'	3
'3903397'	'HUR-00224-17086'	'Reinforced Concrete Slab(1), Wearing Surfaces(2), '	'$46K'	2
'3900304'	'HUR-00018-21685'	'Reinforced Concrete Slab(1), Abutment Reinforced Concrete(1), Metal Bridge Railing(2), '	'$43K'	3
'7001355'	'RIC-00030-14077'	'Girder/Beam Steel(1), Steel Protective Coating(1), '	'$43K'	4
'5207290'	'MED-00271-03080'	'Culvert Reinforced Concrete(1), '	'$41K'	1
'5204143'	'MED-00071-24015'	'Steel Protective Coating(1), '	'$40K'	5
'8502765'	'WAY-00057-11728'	'Steel Protective Coating(1), Abutment Reinforced Concrete(1), '	'$40K'	5
'5200482'	'MED-00018-01719'	'Reinforced Concrete Slab(1), Abutment Reinforced Concrete(2), Wearing Surfaces(1), '	'$40K'	3
'0304808'	'ASD-00250-11618'	'Reinforced Concrete Slab(1), Wearing Surfaces(1), '	'$38K'	2
'5200547'	'MED-00018-02420'	'Reinforced Concrete Slab(1), Abutment Reinforced Concrete(1), Wearing Surfaces(2), '	'$37K'	3
'5200512'	'MED-00018-01929'	'Reinforced Concrete Slab(1), Abutment Reinforced	'$34K'	3

		Concrete(1), Wearing Surfaces(2), '		
'5204747'	'MED-00076-05938'	'Reinforced Concrete Slab(1), Wearing Surfaces(1), '	'$32K'	2
'5204771'	'MED-00076-05938'	'Reinforced Concrete Slab(1), Abutment Reinforced Concrete(1), '	'$32K'	2
'7002882'	'RIC-00042-11948'	'Metal Bridge Railing(1), Pier Wall reinforced Concrete(1), Abutment Reinforced Concrete(1), '	'$30K'	2
'4729803'	'LOR-0080K-18856'	'Culvert Reinforced Concrete(1), '	'$29K'	1
'8501440'	'WAY-00030-01000'	'Strip Seal Expansion Joint(2), Steel Protective Coating(1), '	'$29K'	3
'5207231'	'MED-00271-02349'	'Girder/Beam Steel(1), Steel Protective Coating(1), Columns Reinforced Concrete(1), '	'$27K'	3
'7003919'	'RIC-00071-07118'	'Reinforced Concrete Bridge Railing(1), Girder/Beam Prestressed Concrete(1), '	'$27K'	2
'8501785'	'WAY-00030-09348'	'Reinforced Concrete Slab(1), Abutment Reinforced Concrete(1), '	'$25K'	2
'8504830'	'WAY-00250-19286'	'Reinforced Concrete Slab(1), Columns Reinforced Concrete(1), Abutment Reinforced Concrete(1), Wearing Surfaces(2), '	'$24K'	3
'0302554'	'ASD-00071-04619'	'Culvert Reinforced Concrete(1), '	'$22K'	1
'4729366'	'LOR-0080K-12178'	'Columns Reinforced Concrete(1), Pier Cap Reinforced Concrete(1), '	'$21K'	1
'7001142'	'RIC-00030-11328'	'Abutment Reinforced Concrete(1), Pier Cap Reinforced Concrete(1), '	'$21K'	1
'0300454'	'ASD-00030-05869'	'Abutment Reinforced Concrete(1), '	'$20K'	1

'0300578'	'ASD-00030-09318'	'Steel Protective Coating(1), Abutment Reinforced Concrete(1), '	'$20K'	2
'0300608'	'ASD-00030-09318'	'Steel Protective Coating(1), Abutment Reinforced Concrete(1), '	'$20K'	2
'0300691'	'ASD-00030-11937'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'0304778'	'ASD-00250-10868'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'1701509'	'CRA-00030-08628'	'Strip Seal Expansion Joint(1), Abutment Reinforced Concrete(1), '	'$20K'	2
'1701592'	'CRA-00030-08968'	'Strip Seal Expansion Joint(1), '	'$20K'	1
'2200635'	'ERI-00002-09208'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'2200694'	'ERI-00002-09208'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'2204800'	'ERI-00002-25804'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'2204819'	'ERI-00002-25804'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'2204851'	'ERI-00002-26794'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'3900398'	'HUR-00018-24625'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'3900452'	'HUR-00018-25144'	'Wearing Surfaces(1), '	'$20K'	1
'3900967'	'HUR-00020-11228'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'3900991'	'HUR-00020-11228'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'3903222'	'HUR-00224-01130'	'Reinforced Concrete Slab(1), Abutment Reinforced Concrete(1), '	'$20K'	2
'4700090'	'LOR-00002-06459'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'4700120'	'LOR-00002-06459'	'Abutment Reinforced Concrete(1), '	'$20K'	1

'4702220'	'LOR-00020-20475'	'Arch Masonry(1), Abutment Masonry(1), '	'$20K'	2
'4702255'	'LOR-00020-22655'	'Culvert Masonry(2), '	'$20K'	1
'4702344'	'LOR-00020-24995'	'Culvert Masonry(1), '	'$20K'	1
'4704959'	'LOR-00090-18606'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'4704983'	'LOR-00090-18606'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'4708474'	'LOR-00010-04359'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'4708482'	'LOR-00010-04359'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'5204593'	'MED-00076-02709'	'Columns Reinforced Concrete(1), '	'$20K'	1
'5204801'	'MED-00076-06619'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'7000162'	'RIC-00013-02659'	'Girder/Beam Prestressed Concrete Box(1), '	'$20K'	1
'7001231'	'RIC-00030-12188'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'7002971'	'RIC-00042-16287'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'7003099'	'RIC-0042D-00340'	'Culvert Masonry(2), '	'$20K'	1
'7003730'	'RIC-00071-06409'	'Reinforced Concrete Bridge Railing(1), '	'$20K'	1
'7004699'	'RIC-00071-18776'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'8501688'	'WAY-00030-08918'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'8501718'	'WAY-00030-08918'	'Abutment Reinforced Concrete(1), Pier Cap Reinforced Concrete(1), '	'$20K'	1
'8501815'	'WAY-00030-10388'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'8502285'	'WAY-00030-21255'	'Columns Reinforced Concrete(1), '	'$20K'	1

'8502617'	'WAY-00057-04319'	'Reinforced Concrete Slab(1), Metal Bridge Railing(1), '	'$20K'	2
'8504695'	'WAY-00250-01200'	'Abutment Reinforced Concrete(1), '	'$20K'	1
'8504768'	'WAY-00250-14057'	'Columns Reinforced Concrete(1), '	'$20K'	2
'8504776'	'WAY-00250-17306'	'Columns Reinforced Concrete(1), Abutment Reinforced Concrete(1), '	'$20K'	1
'8504814'	'WAY-00250-18146'	'Steel Protective Coating(2), '	'$20K'	1
'8505977'	'WAY-00585-05779'	'Abutment Reinforced Concrete(1), '	'$20K'	1
All Bridges	-	Total Agency Cost (MR&R+AEM+MOT)	$14,344K	-

(1): All portions of the element that are in condition-state 3 and 4 should be repaired to be improved to at least condition-state 2.

(2): All portions of the element that are in condition-state 3 and 4 should be repaired to be improved to at least condition-state 2, and, if applicable, those quantities of the element in condition-state 2 should receive maintenance/preservation actions.

C.2. Elements contribution to the allocated budget

The results in this section indicates the contribution of elements in the allocated budget.

Table C.2- The contribution of elements in the allocated budget

Element to be Repaired	**Number of Bridges with the Element**	**MR&R Cost on District**	**Percentage of the Total Cost (%)**
Steel Protective Coating	32	$7322K	33.72
Abutment Reinforced Concrete	52	$4345K	20.01
Replace Deck Items	3	$3393K	15.62
Girder/Beam Steel	14	$1841K	8.48
Reinforced Concrete Slab	21	$1035K	4.77
Wearing Surfaces	18	$705K	3.24
Columns Reinforced Concrete	15	$518K	2.38
Reinforced Concrete Deck	2	$433K	1.99
Moveable Bearing (Roller/Sliding)	7	$370K	1.7
Culvert Masonry	3	$360K	1.66
Culvert Reinforced Concrete	5	$237K	1.09
Gusset Plate Steel	2	$214K	0.99
Truss Steel	2	$190K	0.87
Strip Seal Expansion Joint	5	$176K	0.81
Reinforced Concrete Bridge Railing	4	$136K	0.63
Pier Cap Reinforced Concrete	3	$96K	0.44
Metal Bridge Railing	4	$95K	0.44
Girder/Beam Prestressed Concrete Box	1	$72K	0.33
Abutment Masonry	2	$65K	0.3
Arch Masonry	1	$50K	0.23
Pier Wall reinforced Concrete	1	$24K	0.11
Girder/Beam Prestressed Concrete	1	$22K	0.1
Floorbeam Steel	1	$14K	0.06

Appendix D: Computer program and the associated graphical application

In this appendix, the input and modules of the developed computer program for cost and OBCI calculation, as well as the optimal budget allocation are described. In the following sections, the features and capabilities of the graphical application that facilitates a user-friendly interaction with the computer program is illustrated.

D.1. Inputs and modules of the computer program

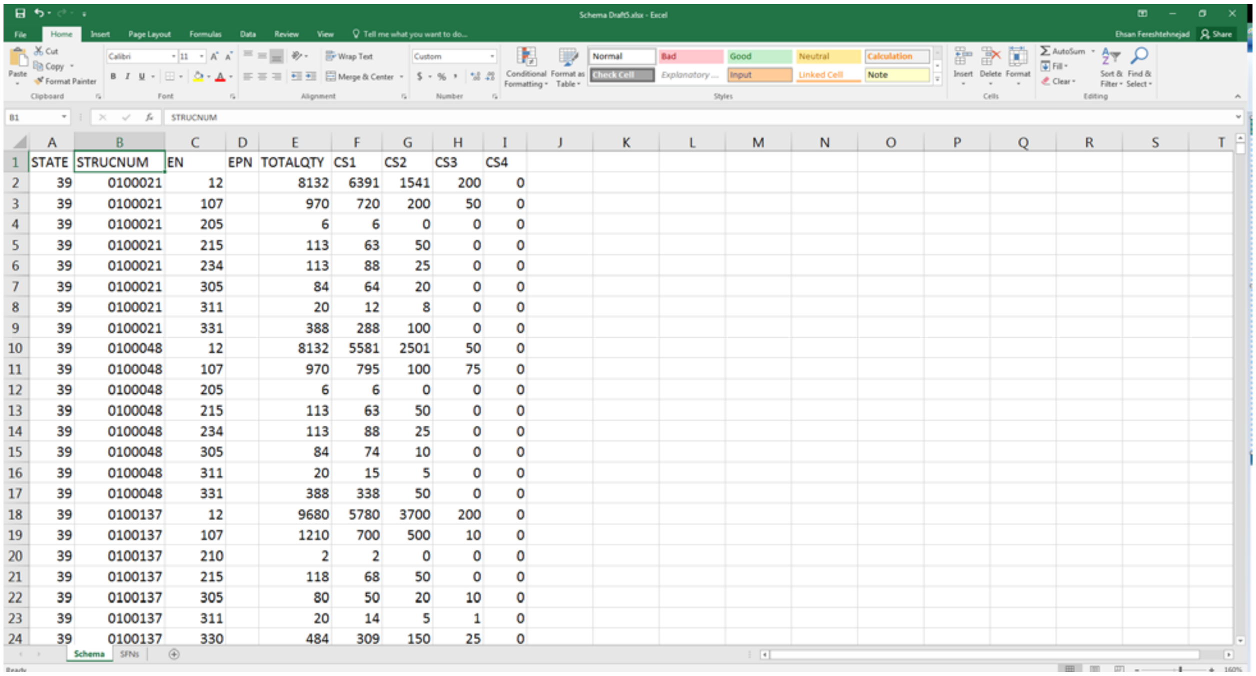
In general, the developed computer program for cost and OBCI calculation, as well as the optimal budget allocation requires the following input files:

- Files that are required yearly from ODOT:
    - An XML/excel file containing element-level inspection results of ODOT’s NHS bridges (see Figure D1).
    - A text file containing NBI information of the entire bridges in Ohio (see Figure D2).
- Permanent files that have been developed by the research team:
    - An excel file containing cost tables for bridge elements of various types and/or materials (see Figure D3).
    - An excel file indicating minimum safe and serviceable thresholds for the condition-state of all bridge elements (see Figure D4).
    - An excel file identifying major elements that are in the load path of bridges (see Figure D5).
    - An excel file presenting Ohio counties in each district (see Figure D6).
    - An excel file presenting the guideline for the above text file that contains NBI information of the entire bridges in Ohio (see Figure D7).
    - An excel file containing various bridge elements with their codes, units of measurement, and the component to which they belong to (see Figure D8).

For an efficient performance, this computer program entails multiple modules. These modules are as follows:

- **Module 1:** sorts and stores county codes of each district.
- **Module 2:** reads the excel file containing NHS bridges and for each bridge, stores elements with their quantities in condition-states 1 to 4.
- **Module 3:** to avoid errors, relates element codes from the input excel file of element-level inspection to elements that exist in a MATLAB code that was initially developed for OBCI calculation.
- **Module 4:** identifies the district of each NHS bridge based on the first two digits of the SFN of each bridge.
- **Module 5:** reads the NBI information of all bridges in Ohio from ODOT’s file reported to FHWA.
- **Module 6:** finds and stores the line of NBI information for an NHS bridge of interest from the output of Module 5.

- **Module 7:** is the main engine of the computer code, which systematically calculates OBCI values and costs of NHS bridges using the outputs of the above modules.
- **Module 8:** generates output results, e.g. graphs, tables, and charts for cost and OBCI values.
- **Module 9:** performs optimal budget allocation based on the outputs of Module 7, which is called to calculate OBCI and cost values for each combination of MR&R actions on elements of all bridges in the portfolio.
- **Module 10:** reports sorted outputs of Module 9, including the optimal actions for the elements of each bridge, the type of these actions, duration estimation of these project, the required agency and user costs for each member of bridges to reach the like-new state after receiving optimal repairs, among others.
- **Module 11:** Calculates element-, component-, bridge-, and network-level OBCI values after performing the optimal repair work plan by calling Module 7.
- **Module 12:** Generates output results, e.g. graphs, tables, and charts of the optimal work plan for bridge engineers and users.



STATE	STRUCNUM	EN	EPN	TOTALQTY	CS1	CS2	CS3	CS4
39	0100021	12		8132	6391	1541	200	0
39	0100021	107		970	720	200	50	0
39	0100021	205		6	6	0	0	0
39	0100021	215		113	63	50	0	0
39	0100021	234		113	88	25	0	0
39	0100021	305		84	64	20	0	0
39	0100021	311		20	12	8	0	0
39	0100021	331		388	288	100	0	0
39	0100048	12		8132	5581	2501	50	0
39	0100048	107		970	795	100	75	0
39	0100048	205		6	6	0	0	0
39	0100048	215		113	63	50	0	0
39	0100048	234		113	88	25	0	0
39	0100048	305		84	74	10	0	0
39	0100048	311		20	15	5	0	0
39	0100048	331		388	338	50	0	0
39	0100137	12		9680	5780	3700	200	0
39	0100137	107		1210	700	500	10	0
39	0100137	210		2	2	0	0	0
39	0100137	215		118	68	50	0	0
39	0100137	305		80	50	20	10	0
39	0100137	311		20	14	5	1	0
39	0100137	330		484	309	150	25	0

Figure D1- A sample of an excel file containing element-level inspection results of ODOT's NHS bridges

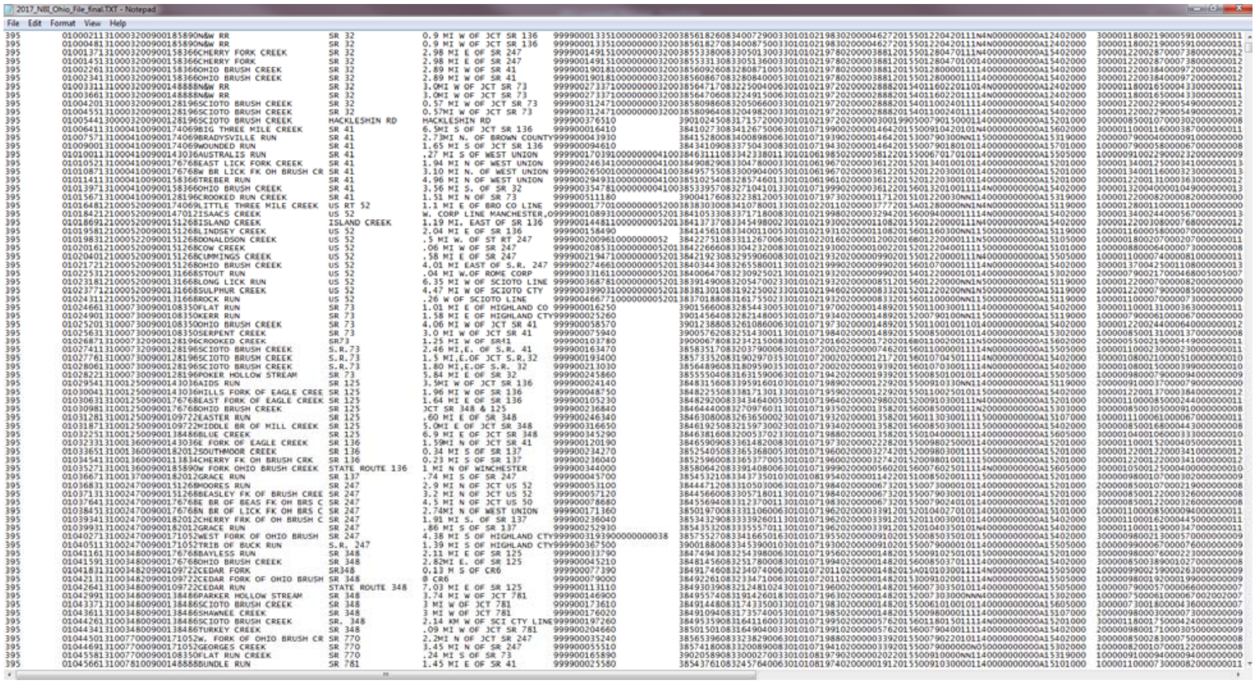
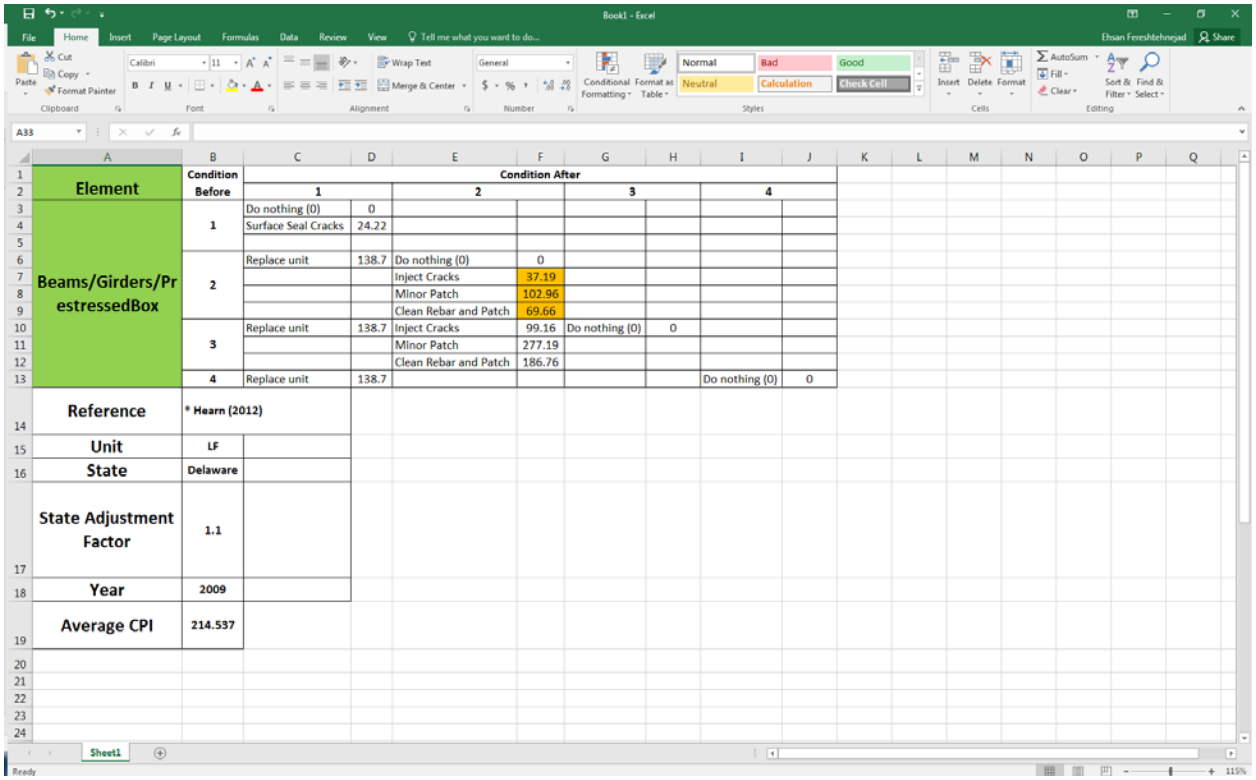
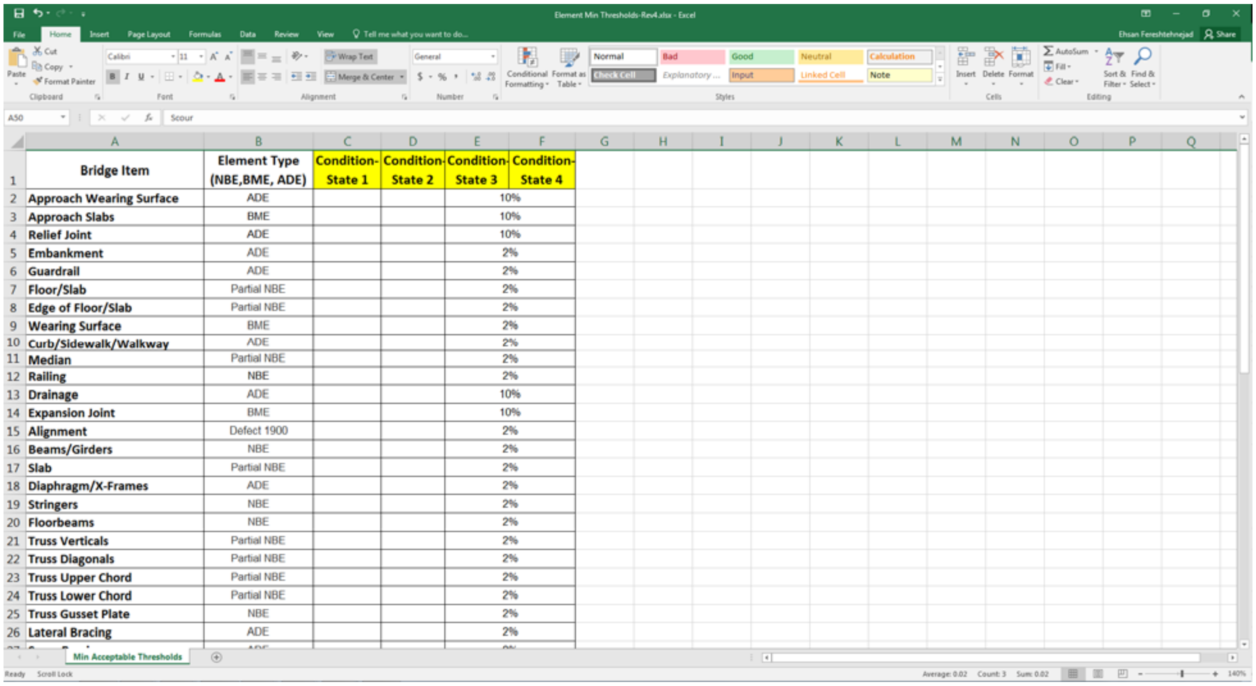


Figure D2- A sample of a text file containing NBI information of the entire bridges in Ohio



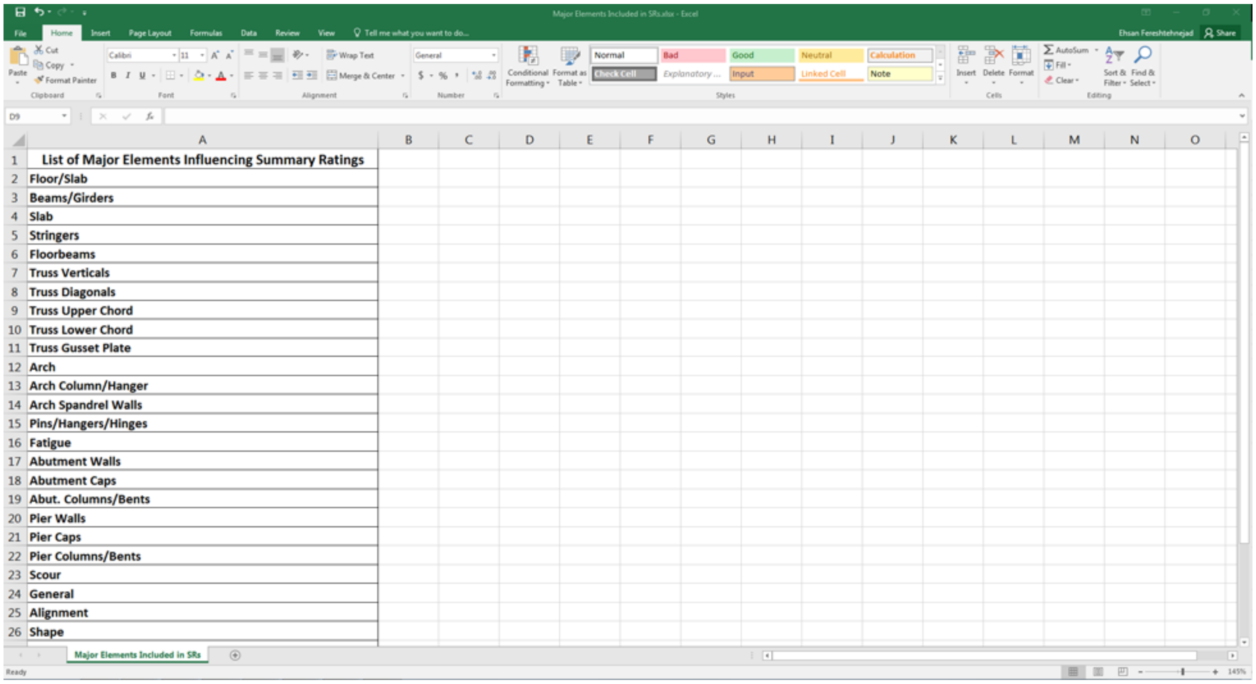
Element	Condition Before	Condition After							
		1		2		3		4	
Beams/Girders/PrestressedBox	1	Do nothing (0)	0						
		Surface Seal Cracks	24.22						
	2	Replace unit	138.7	Do nothing (0)	0				
				Inject Cracks	37.19				
				Minor Patch	102.96				
				Clean Rebar and Patch	69.66				
	3	Replace unit	138.7	Inject Cracks	99.16	Do nothing (0)	0		
				Minor Patch	277.19				
				Clean Rebar and Patch	186.76				
	4	Replace unit	138.7					Do nothing (0)	0
Reference	* Hearn (2012)								
Unit	LF								
State	Delaware								
State Adjustment Factor	1.1								
Year	2009								
Average CPI	214.537								

Figure D3- An excel file containing cost tables for bridge elements of various types and/or materials



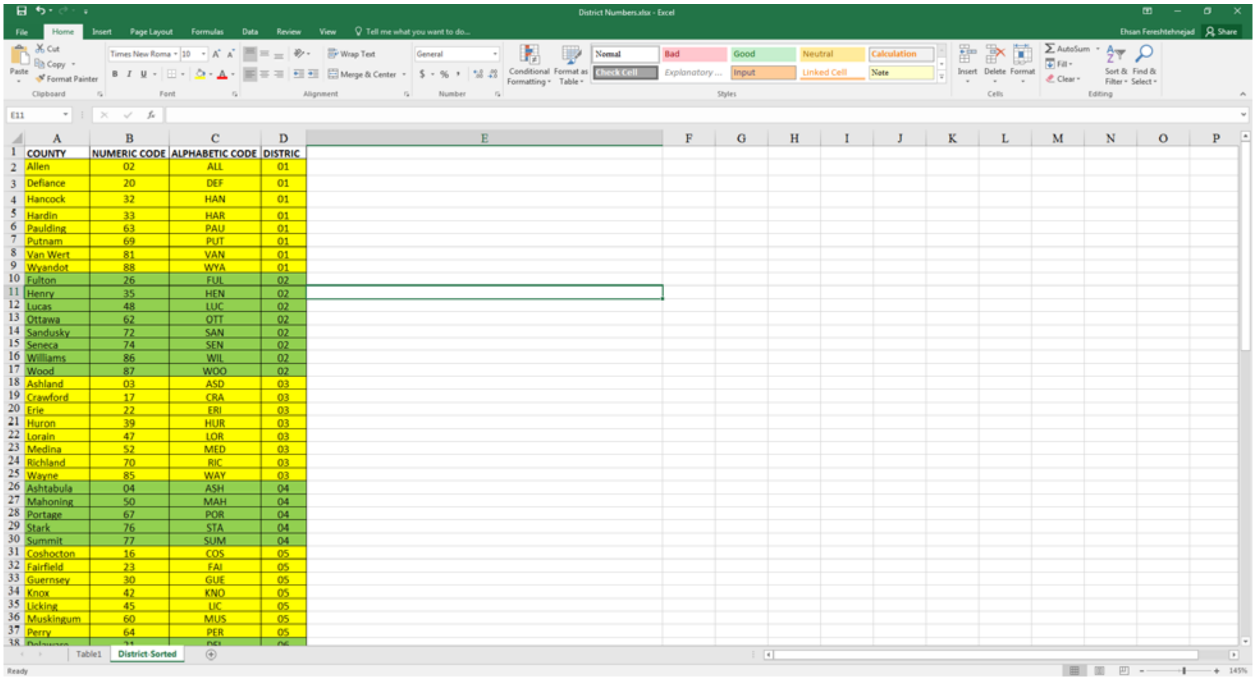
	Bridge Item	Element Type (NBE,BME, ADE)	Condition-State 1	Condition-State 2	Condition-State 3	Condition-State 4
2	Approach Wearing Surface	ADE			10%	
3	Approach Slabs	BME			10%	
4	Relief Joint	ADE			10%	
5	Embankment	ADE			2%	
6	Guardrail	ADE			2%	
7	Floor/Slab	Partial NBE			2%	
8	Edge of Floor/Slab	Partial NBE			2%	
9	Wearing Surface	BME			2%	
10	Curb/Sidewalk/Walkway	ADE			2%	
11	Median	Partial NBE			2%	
12	Railing	NBE			2%	
13	Drainage	ADE			10%	
14	Expansion Joint	BME			10%	
15	Alignment	Defect 1900			2%	
16	Beams/Girders	NBE			2%	
17	Slab	Partial NBE			2%	
18	Diaphragm/X-Frames	ADE			2%	
19	Stringers	NBE			2%	
20	Floorbeams	NBE			2%	
21	Truss Verticals	Partial NBE			2%	
22	Truss Diagonals	Partial NBE			2%	
23	Truss Upper Chord	Partial NBE			2%	
24	Truss Lower Chord	Partial NBE			2%	
25	Truss Gusset Plate	NBE			2%	
26	Lateral Bracing	ADE			2%	

Figure D4- An excel file indicating minimum safe and serviceable thresholds for the condition-state of all bridge elements



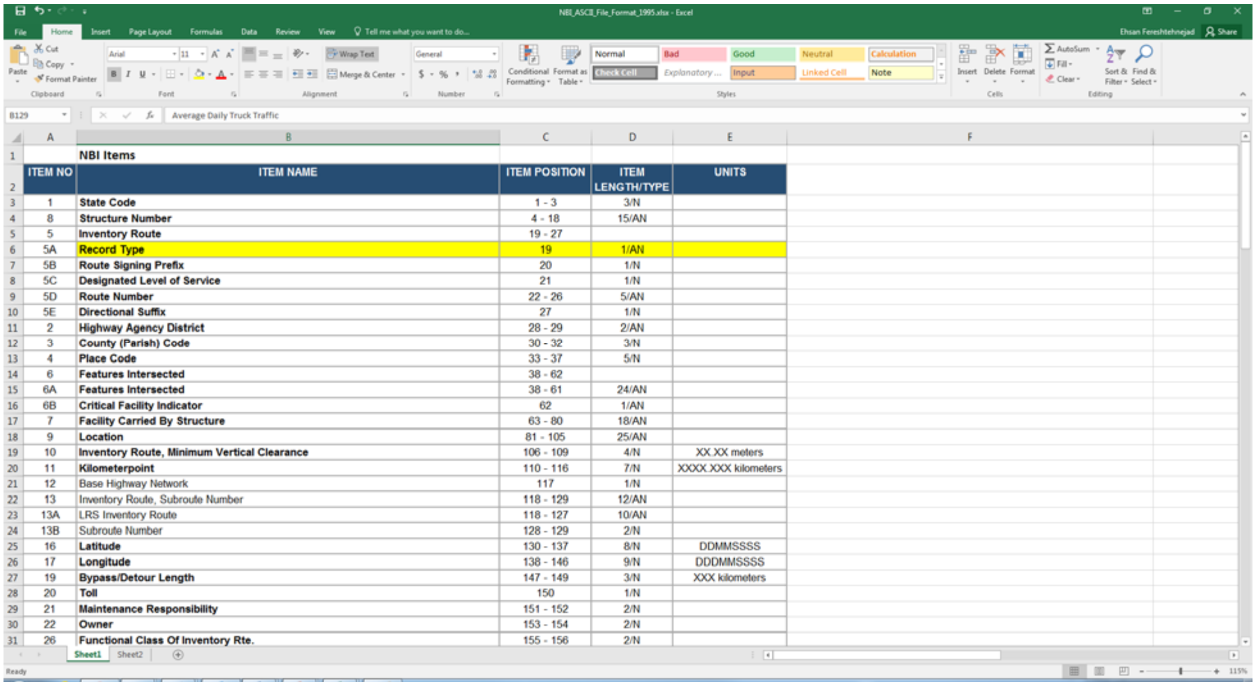
	List of Major Elements Influencing Summary Ratings
2	Floor/Slab
3	Beams/Girders
4	Slab
5	Stringers
6	Floorbeams
7	Truss Verticals
8	Truss Diagonals
9	Truss Upper Chord
10	Truss Lower Chord
11	Truss Gusset Plate
12	Arch
13	Arch Column/Hanger
14	Arch Spandrel Walls
15	Pins/Hangers/Hinges
16	Fatigue
17	Abutment Walls
18	Abutment Caps
19	Abut. Columns/Bents
20	Pier Walls
21	Pier Caps
22	Pier Columns/Bents
23	Scour
24	General
25	Alignment
26	Shape

Figure D5- An excel file identifying major elements that are in the load path of bridges



COUNTY	NUMERIC CODE	ALPHABETIC CODE	DISTRIC
Allen	02	ALL	01
Defiance	20	DEF	01
Hancock	32	HAN	01
Hardin	33	HAR	01
Paulding	63	PAU	01
Putnam	69	PUT	01
Van Wert	81	VAN	01
Wyandot	88	WYA	01
Fulton	26	FUL	02
Henry	35	HEN	02
Lucas	48	LUC	02
Ottawa	62	OTT	02
Sandusky	72	SAN	02
Seneca	74	SEN	02
Williams	86	WIL	02
Wood	87	WOO	02
Ashland	03	ASD	03
Crawford	17	CRA	03
Erie	22	ERI	03
Huron	39	HUR	03
Lorain	47	LOR	03
Medina	52	MED	03
Richland	70	RIC	03
Wayne	85	WAY	03
Ashtabula	04	ASH	04
Mahoning	50	MAH	04
Portage	67	POR	04
Stark	76	STA	04
Summit	77	SUM	04
Coshocton	16	COS	05
Fairfield	23	FAI	05
Guernsey	30	GUE	05
Knox	42	KNO	05
Licking	45	LIC	05
Muskingum	60	MUS	05
Perry	64	PER	05

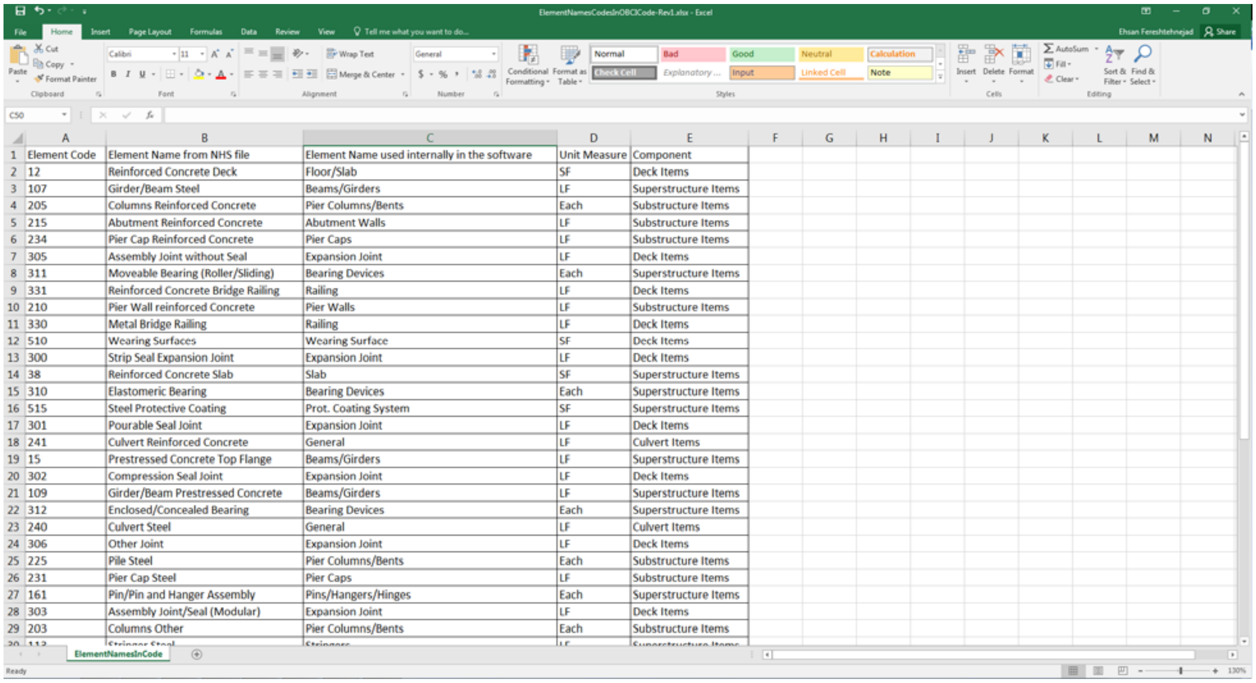
Figure D6- An excel file presenting Ohio counties in each district



NBI Items

ITEM NO	ITEM NAME	ITEM POSITION	ITEM LENGTH/TYPE	UNITS
1	**State Code**	1 - 3	3/N	
8	**Structure Number**	4 - 18	15/AN	
5	**Inventory Route**	19 - 27		
5A	**Record Type**	19	1/AN	
5B	**Route Signing Prefix**	20	1/N	
5C	**Designated Level of Service**	21	1/N	
5D	**Route Number**	22 - 26	5/AN	
5E	**Directional Suffix**	27	1/N	
2	**Highway Agency District**	28 - 29	2/AN	
3	**County (Parish) Code**	30 - 32	3/N	
4	**Place Code**	33 - 37	5/N	
6	**Features Intersected**	38 - 62		
6A	**Features Intersected**	38 - 61	24/AN	
6B	**Critical Facility Indicator**	62	1/AN	
7	**Facility Carried By Structure**	63 - 80	18/AN	
9	**Location**	81 - 105	25/AN	
10	**Inventory Route, Minimum Vertical Clearance**	106 - 109	4/N	XX.XX meters
11	**Kilometerpoint**	110 - 116	7/N	XXXX.XXX kilometers
12	Base Highway Network	117	1/N	
13	Inventory Route, Subroute Number	118 - 129	12/AN	
13A	LRS Inventory Route	118 - 127	10/AN	
13B	Subroute Number	128 - 129	2/N	
16	**Latitude**	130 - 137	8/N	DDMMSSSS
17	**Longitude**	138 - 146	9/N	DDDMMSSSS
19	**Bypass/Detour Length**	147 - 149	3/N	XXX kilometers
20	**Toll**	150	1/N	
21	**Maintenance Responsibility**	151 - 152	2/N	
22	**Owner**	153 - 154	2/N	
26	**Functional Class Of Inventory Rte.**	155 - 156	2/N	

Figure D7- An excel file presenting the guideline for the above text file that contains NBI information of the entire bridges in Ohio



Element Code	Element Name from NHS file	Element Name used internally in the software	Unit Measure	Component
12	Reinforced Concrete Deck	Floor/Slab	SF	Deck Items
107	Girder/Beam Steel	Beams/Girders	LF	Superstructure Items
205	Columns Reinforced Concrete	Pier Columns/Bents	Each	Substructure Items
215	Abutment Reinforced Concrete	Abutment Walls	LF	Substructure Items
234	Pier Cap Reinforced Concrete	Pier Caps	LF	Substructure Items
305	Assembly Joint without Seal	Expansion Joint	LF	Deck Items
311	Moveable Bearing (Roller/Sliding)	Bearing Devices	Each	Superstructure Items
331	Reinforced Concrete Bridge Railing	Railing	LF	Deck Items
210	Pier Wall reinforced Concrete	Pier Walls	LF	Substructure Items
330	Metal Bridge Railing	Railing	LF	Deck Items
510	Wearing Surfaces	Wearing Surface	SF	Deck Items
300	Strip Seal Expansion Joint	Expansion Joint	LF	Deck Items
38	Reinforced Concrete Slab	Slab	SF	Superstructure Items
310	Elastomeric Bearing	Bearing Devices	Each	Superstructure Items
515	Steel Protective Coating	Prot. Coating System	SF	Superstructure Items
301	Pourable Seal Joint	Expansion Joint	LF	Deck Items
241	Culvert Reinforced Concrete	General	LF	Culvert Items
15	Prestressed Concrete Top Flange	Beams/Girders	LF	Superstructure Items
302	Compression Seal Joint	Expansion Joint	LF	Deck Items
109	Girder/Beam Prestressed Concrete	Beams/Girders	LF	Superstructure Items
312	Enclosed/Concealed Bearing	Bearing Devices	Each	Superstructure Items
240	Culvert Steel	General	LF	Culvert Items
306	Other Joint	Expansion Joint	LF	Deck Items
225	Pile Steel	Pier Columns/Bents	Each	Substructure Items
231	Pier Cap Steel	Pier Caps	LF	Substructure Items
161	Pin/Pin and Hanger Assembly	Pins/Hangers/Hinges	Each	Superstructure Items
303	Assembly Joint/Seal (Modular)	Expansion Joint	LF	Deck Items
203	Columns Other	Pier Columns/Bents	Each	Substructure Items

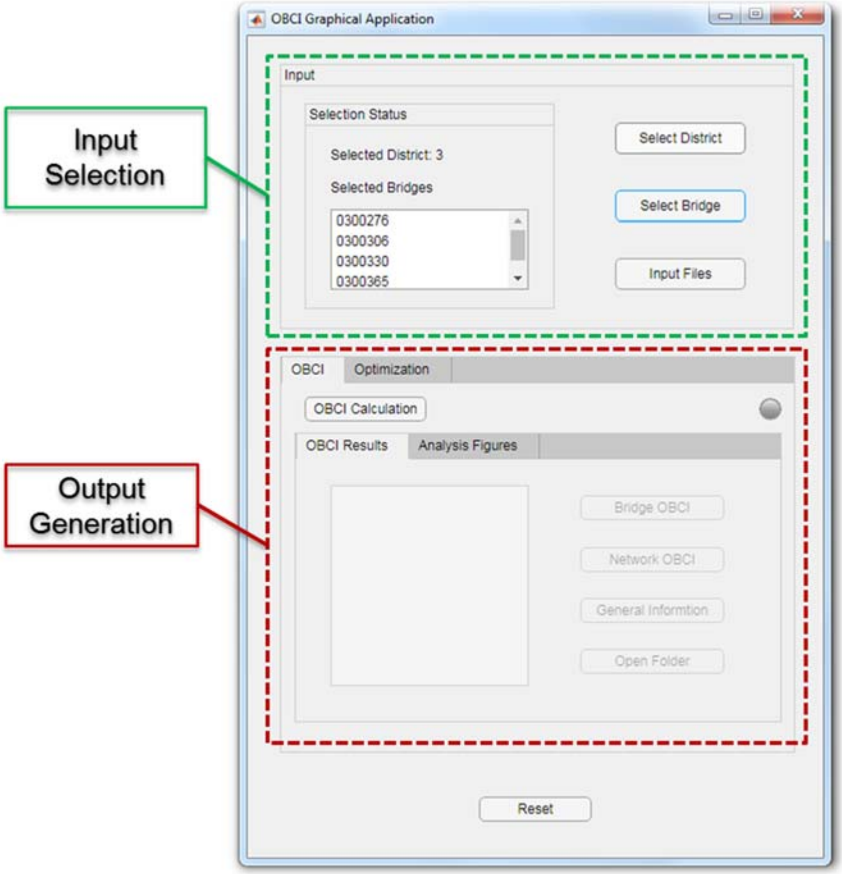
Figure D8- An excel file containing various bridge elements with their codes, units of measurement, and the component, to which they belong to

D.2. Illustration of the graphical application

The MATLAB code for the calculation and optimization of OBCI developed by the OSU research team contains thousands of lines and multiple modules. If the user of the code wants to get a specific type of output for a specific bridge or a specific portfolio of bridges, the user needs to make modifications to multiple parameters in multiple locations of the code. Due to the complexity of the code, this is a time-consuming process and may lead to errors. In addition, it requires a full understanding of the MATLAB code in order to make the modifications. To solve this problem, a graphical application is developed that allows the user to fully interact with the code without any difficulties. This user-friendly graphical application grants the user the permissions for selecting a bridge or multiple bridges, performing the OBCI calculation or the optimization and selecting the type of the outputs to generate.

The development of the graphical application has two parts—the layout design and coding. The objective of the former is to design the layout of the buttons and windows in a way that the user can easily understand their functions and keep track of the progress of the calculation and optimization. The objective of the latter is to integrate the MATLAB code for the calculation and optimization of OBCI with the buttons and windows. Although the code for the calculation and optimization of OBCI has been developed, the graphical application cannot directly use the code, as the structures of the code and data sharing methods are different. Therefore, coding is still an essential part in the development of the graphical application.

The graphical interface is developed in the App Designer tool in MATLAB 2018a. The details of this new Graphical User Interface (GUI) is discussed in the rest of this section. Figure D9 shows the main window of the GUI. As shown in the figure, the main window can be divided into two parts—input selection and output generation. In input selection, the user can choose the target(s) of the analysis, such as a district, a bridge and a portfolio of bridges. The user can also make modifications to the input files.



Selected District: 3

Selected Bridges

0300276
0300306
0300330
0300365

Figure D9- Main window

When the user clicks on the ‘Select District’ button, a new window will pop up and let user choose a district from the 12 districts in Ohio as shown in Figure D10. The user can click on ‘OK’ to confirm or ‘Cancel’ to cancel all the selections. After the selection, the selected district will be displayed in the selection status panel as shown in Figure D9.

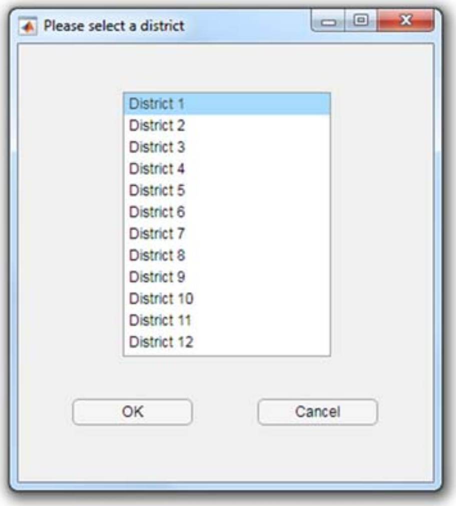
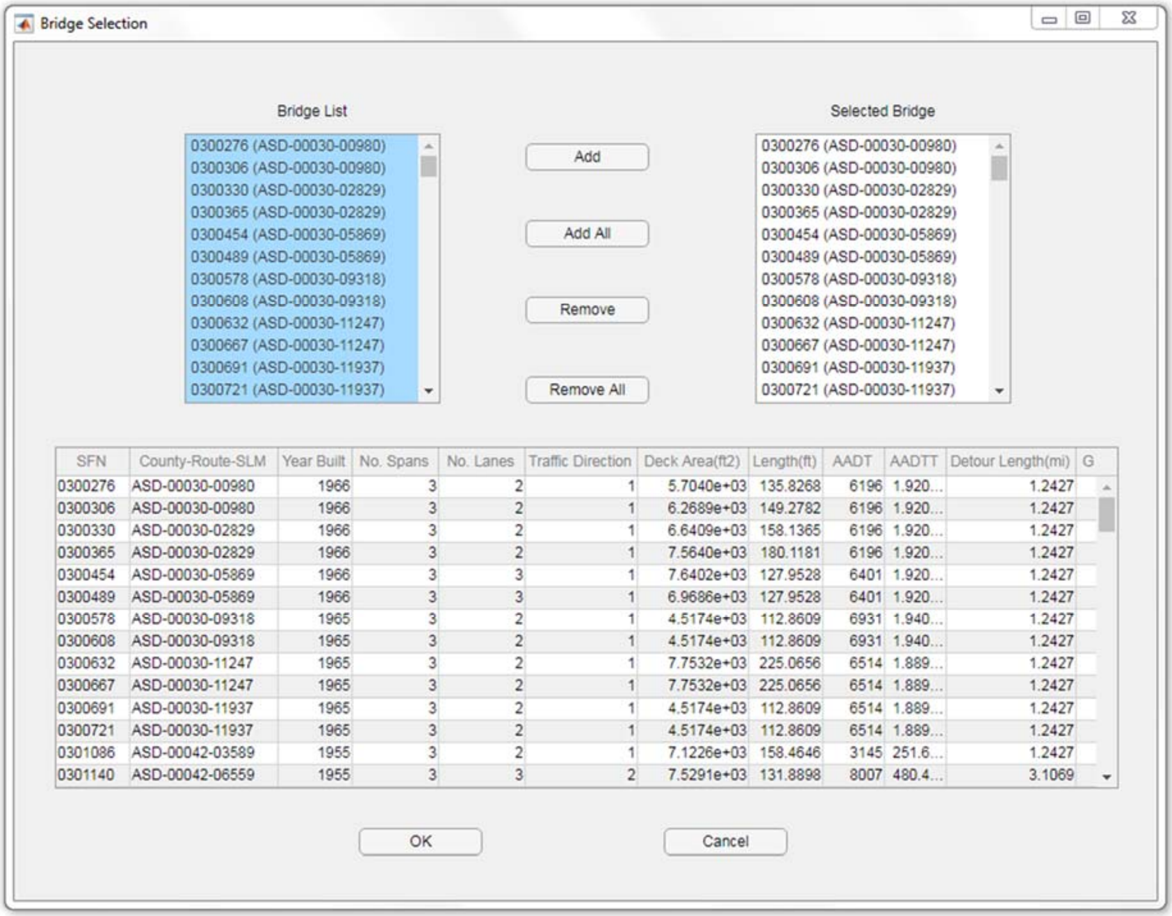


Figure D10- District selection window



Bridge List

0300276 (ASD-00030-00980)
0300306 (ASD-00030-00980)
0300330 (ASD-00030-02829)
0300365 (ASD-00030-02829)
0300454 (ASD-00030-05869)
0300489 (ASD-00030-05869)
0300578 (ASD-00030-09318)
0300608 (ASD-00030-09318)
0300632 (ASD-00030-11247)
0300667 (ASD-00030-11247)
0300691 (ASD-00030-11937)
0300721 (ASD-00030-11937)

Selected Bridge

0300276 (ASD-00030-00980)
0300306 (ASD-00030-00980)
0300330 (ASD-00030-02829)
0300365 (ASD-00030-02829)
0300454 (ASD-00030-05869)
0300489 (ASD-00030-05869)
0300578 (ASD-00030-09318)
0300608 (ASD-00030-09318)
0300632 (ASD-00030-11247)
0300667 (ASD-00030-11247)
0300691 (ASD-00030-11937)
0300721 (ASD-00030-11937)

SFN	County-Route-SLM	Year Built	No. Spans	No. Lanes	Traffic Direction	Deck Area(ft2)	Length(ft)	AADT	AADTT	Detour Length(mi)	G
0300276	ASD-00030-00980	1966	3	2	1	5.7040e+03	135.8268	6196	1.920...	1.2427	
0300306	ASD-00030-00980	1966	3	2	1	6.2689e+03	149.2782	6196	1.920...	1.2427	
0300330	ASD-00030-02829	1966	3	2	1	6.6409e+03	158.1365	6196	1.920...	1.2427	
0300365	ASD-00030-02829	1966	3	2	1	7.5640e+03	180.1181	6196	1.920...	1.2427	
0300454	ASD-00030-05869	1966	3	3	1	7.6402e+03	127.9528	6401	1.920...	1.2427	
0300489	ASD-00030-05869	1966	3	3	1	6.9686e+03	127.9528	6401	1.920...	1.2427	
0300578	ASD-00030-09318	1965	3	2	1	4.5174e+03	112.8609	6931	1.940...	1.2427	
0300608	ASD-00030-09318	1965	3	2	1	4.5174e+03	112.8609	6931	1.940...	1.2427	
0300632	ASD-00030-11247	1965	3	2	1	7.7532e+03	225.0656	6514	1.889...	1.2427	
0300667	ASD-00030-11247	1965	3	2	1	7.7532e+03	225.0656	6514	1.889...	1.2427	
0300691	ASD-00030-11937	1965	3	2	1	4.5174e+03	112.8609	6514	1.889...	1.2427	
0300721	ASD-00030-11937	1965	3	2	1	4.5174e+03	112.8609	6514	1.889...	1.2427	
0301086	ASD-00042-03589	1955	3	2	1	7.1226e+03	158.4646	3145	251.6...	1.2427	
0301140	ASD-00042-06559	1955	3	3	2	7.5291e+03	131.8898	8007	480.4...	3.1069	

Figure D11- Bridge selection window

In this bridge selection window, the user can select a bridge or multiple bridges. The top-left combo box lists all the bridges in the selected district. When the user clicks on the ‘Add’ button after selecting a bridge or multiple bridges (hold *Ctrl* to select multiple bridges), the selected bridge or bridges will be displayed in the top-right combo box. In addition, the user can check the general information of selected bridges in the combo box at the bottom. The user can click on ‘OK’ to confirm or ‘Cancel’ to cancel all the selections. After the selection, the selected bridge or bridges will be displayed in the selection status panel as shown in Figure D11.

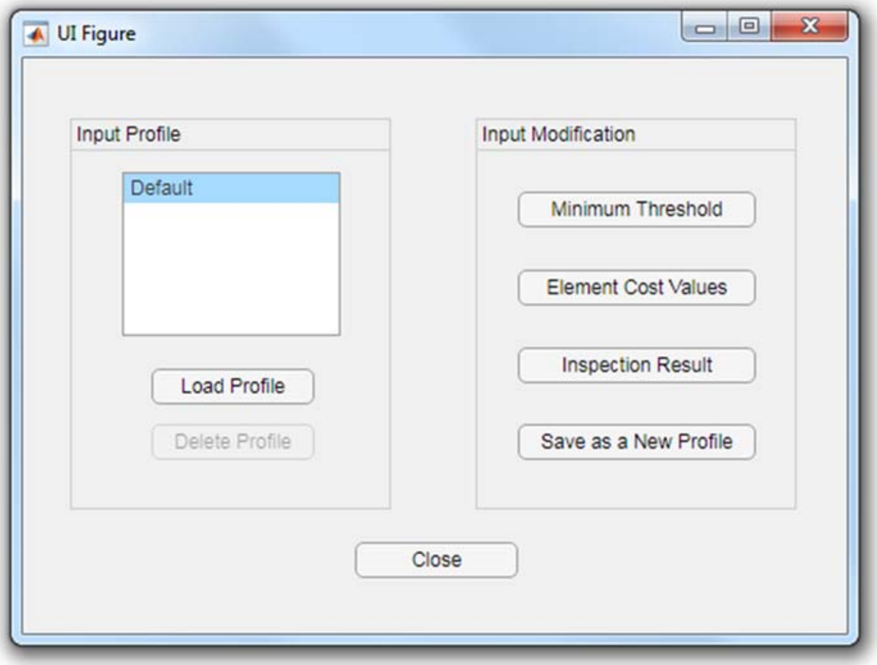


Figure D12- Input files window

In the right part of input files window, as shown in Figure D12, the user is able to modify input files, such as minimum threshold, element costs values and inspection result. The user is also able to save the modified input files as a profile that can be loaded later. In the left side of the window, the user is able to manage the profiles and perform actions, such as loading profile and deleting profile. Note that the default profile is non-removable. The user can load the default profile at any time.

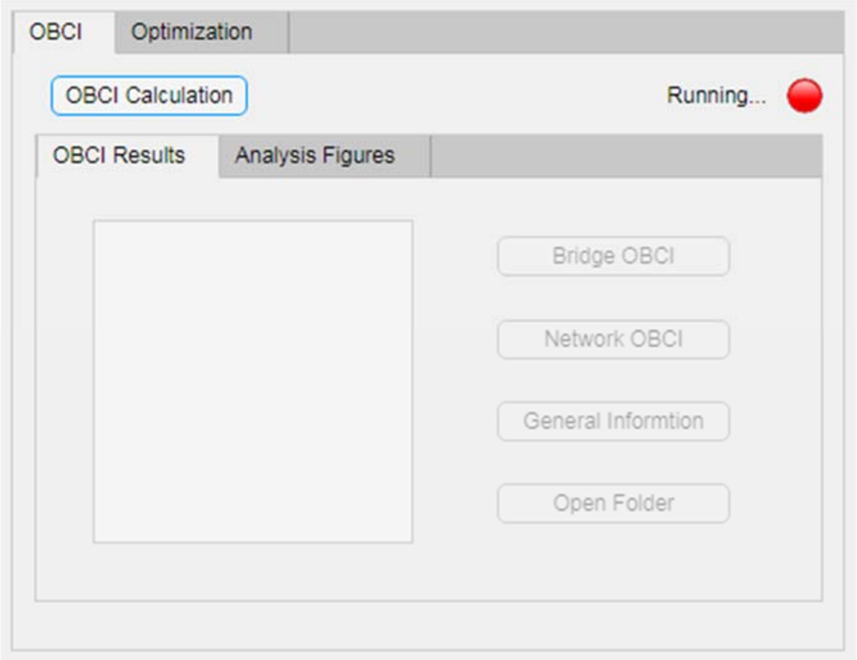
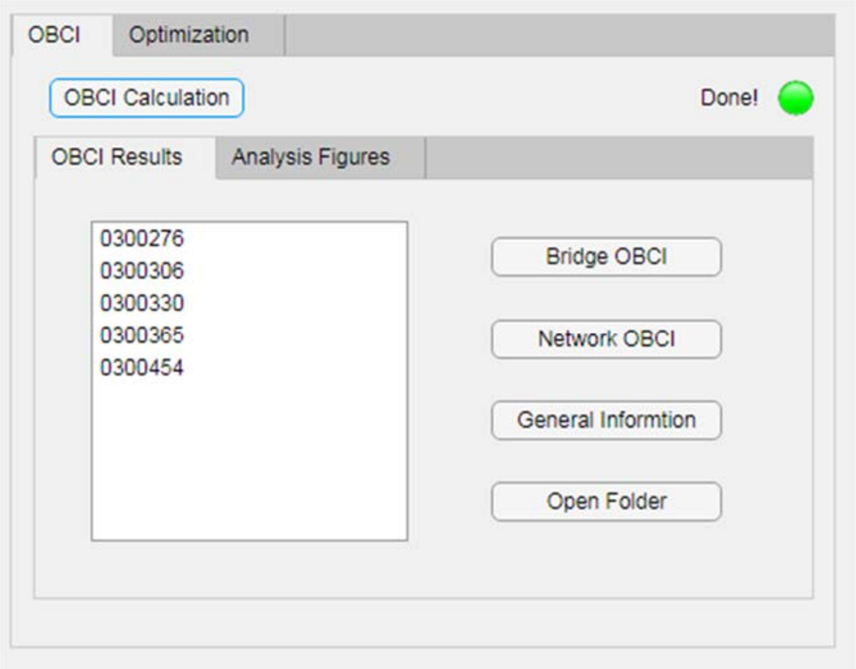


Figure D13- OBCI tab (running)

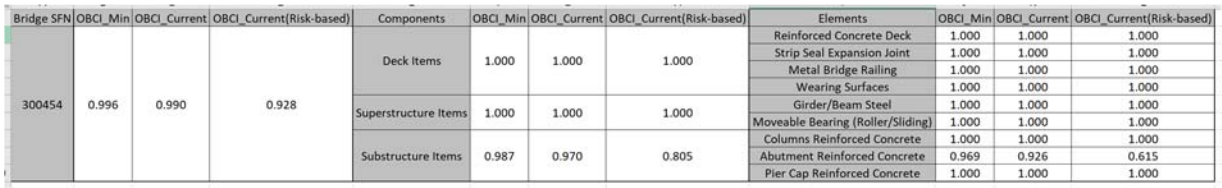
The output generation has two tabs. They are for OBCI calculation and optimization, respectively. The OBCI calculation part is able to calculate the OBCI for the target(s) and generate the output. When the user has selected the target(s), the user can click on the ‘OBCI Calculation’ button, which is disabled before. As shown in Figure D13, the light next to the button indicates the status of the calculation. When the calculation is in progress, the light is red with a label that says ‘running…’. When the calculation is done, the light turns green and the dropdown button under the calculation button is enabled. Then, there are two tabs for the user to select—‘OBCI Results’ and ‘Analysis Figures’ as shown in Figure D14.



0300276
0300306
0300330
0300365
0300454

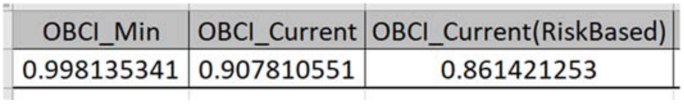
Figure D14- OBCI tab (done)

In the ‘OBCI Results’ tab, there is a list that contains all the target bridges (E.g. bridges with file numbers of 0300454, 0300365, 0300330, 0300306 and 0300276). The user can select a bridge from the list and then click on ‘Bridge OBCI’ on the right, which opens an excel file that contains all OBCI information for this bridge as shown in Figure D15. ‘Network OBCI’ opens an excel file that contains the network-level OBCI of all the bridges as shown in Figure D16. ‘General Information’ opens an excel file that contains the general information of all the bridges as shown in Figure D17. The user can open the folder that contains all the aforementioned excel files by clicking on ‘Open Folder’.



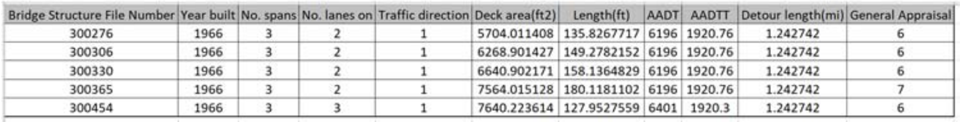
Bridge SFN	OBCI_Min	OBCI_Current	OBCI_Current(Risk-based)	Components	OBCI_Min	OBCI_Current	OBCI_Current(Risk-based)	Elements	OBCI_Min	OBCI_Current	OBCI_Current(Risk-based)
300454	0.996	0.990	0.928	Deck Items	1.000	1.000	1.000	Reinforced Concrete Deck	1.000	1.000	1.000
								Strip Seal Expansion Joint	1.000	1.000	1.000
								Metal Bridge Railing	1.000	1.000	1.000
								Wearing Surfaces	1.000	1.000	1.000
				Superstructure Items	1.000	1.000	1.000	Girder/Beam Steel	1.000	1.000	1.000
								Moveable Bearing (Roller/Sliding)	1.000	1.000	1.000
				Substructure Items	0.987	0.970	0.805	Columns Reinforced Concrete	1.000	1.000	1.000
								Abutment Reinforced Concrete	0.969	0.926	0.615
								Pier Cap Reinforced Concrete	1.000	1.000	1.000

Figure D15- OBCI excel file for a single bridge



OBCI_Min	OBCI_Current	OBCI_Current(RiskBased)
0.998135341	0.907810551	0.861421253

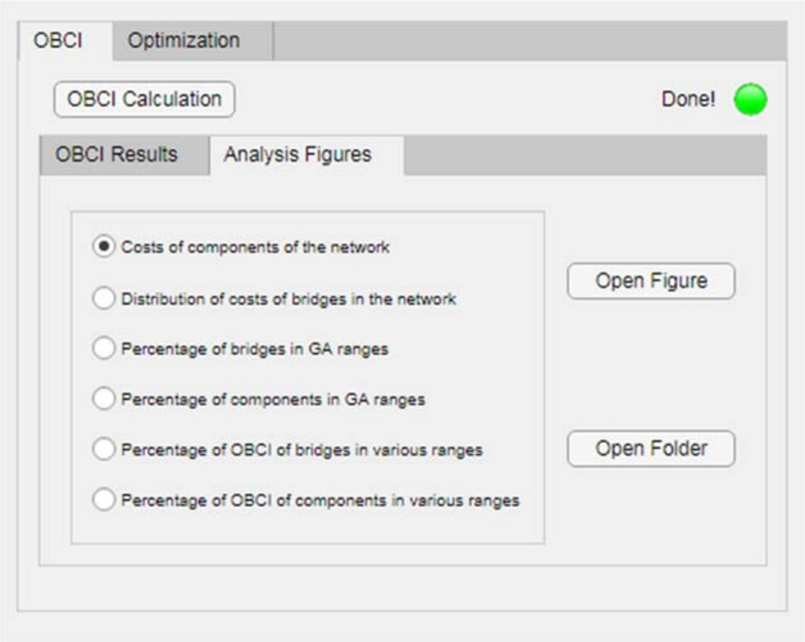
Figure D16- Network-level OBCI excel file



Bridge Structure File Number	Year built	No. spans	No. lanes on	Traffic direction	Deck area(ft2)	Length(ft)	AADT	AADTT	Detour length(mi)	General Appraisal
300276	1966	3	2	1	5704.011408	135.8267717	6196	1920.76	1.242742	6
300306	1966	3	2	1	6268.901427	149.2782152	6196	1920.76	1.242742	6
300330	1966	3	2	1	6640.902171	158.1364829	6196	1920.76	1.242742	6
300365	1966	3	2	1	7564.015128	180.1181102	6196	1920.76	1.242742	7
300454	1966	3	3	1	7640.223614	127.9527559	6401	1920.3	1.242742	6

Figure D17- Bridges General Information excel file

The ‘Analysis Figures’ tab contains all figure results generated by the code. All figures are generated in two file formats—emf and png. The figures include costs of component of the network, distribution of costs of bridges in the network, percentage of bridges in GA ranges, percentage of components in GA ranges, percentage of $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$ of bridges in various ranges and Percentage of components in various ranges of $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$. As shown in Figure D18, the user can select an option in the radio button group and click on ‘Open Figure’ on the right, then the selected figure will pop up. The user can also open the folder that contains all figures by clicking on ‘Open Folder’. All the figures for the five bridges are presented in Figure D19~D24.



● Costs of components of the network
○ Distribution of costs of bridges in the network
○ Percentage of bridges in GA ranges
○ Percentage of components in GA ranges
○ Percentage of OBCI of bridges in various ranges
○ Percentage of OBCI of components in various ranges

Figure D18- Analysis Figures

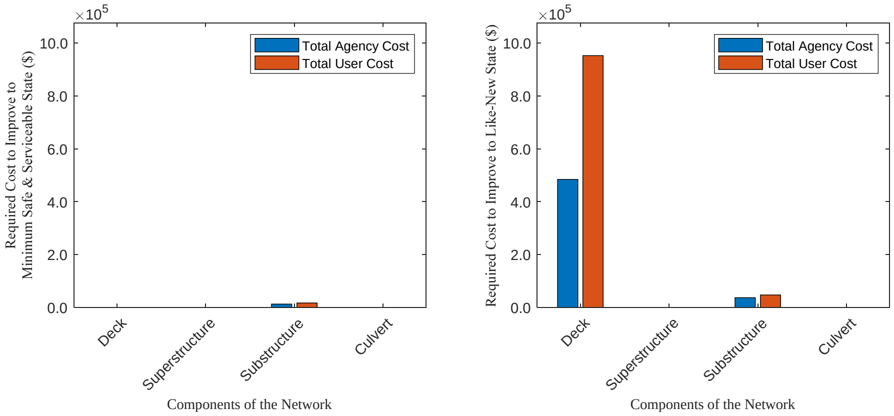


Figure D19- Costs of components of the network

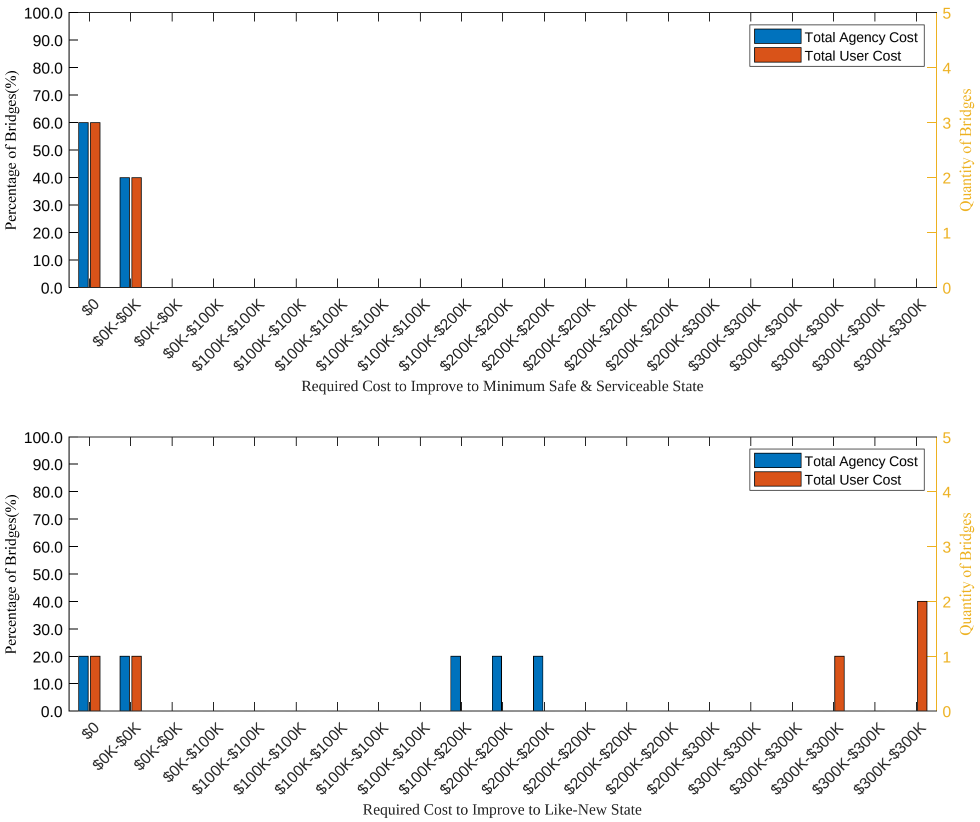


Figure D20- Distribution of costs of bridges in the network

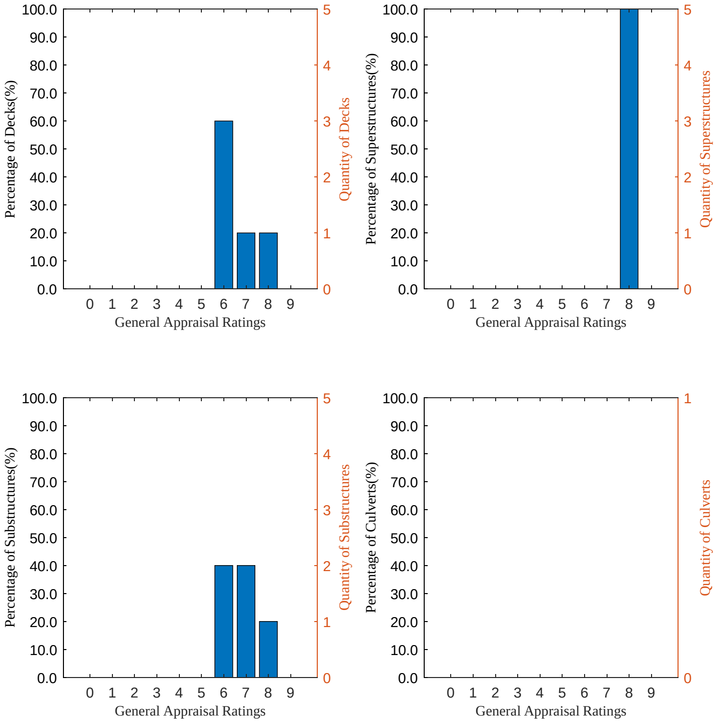


Figure D21- Percentage of components in GA ranges

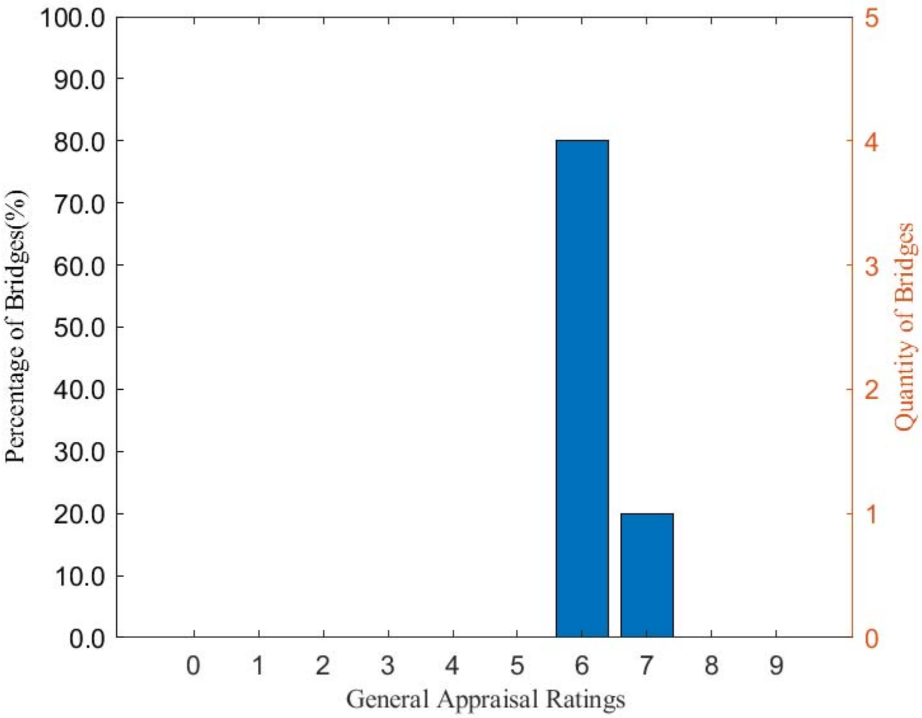


Figure D22- Percentage of bridges in GA ranges

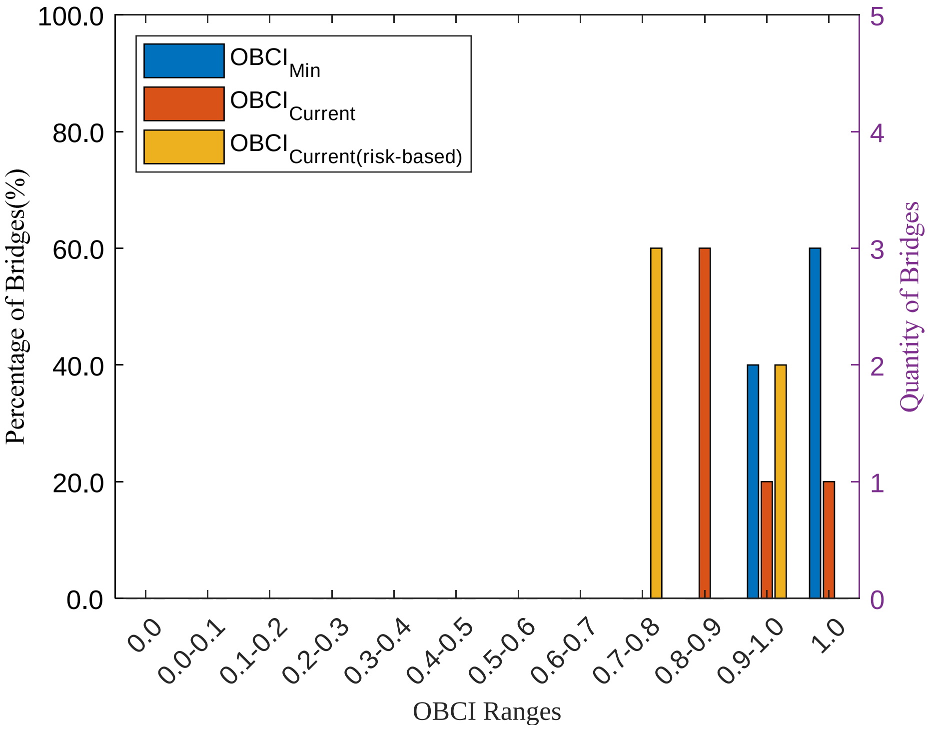


Figure D23- Percentage of bridges in various ranges of $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$

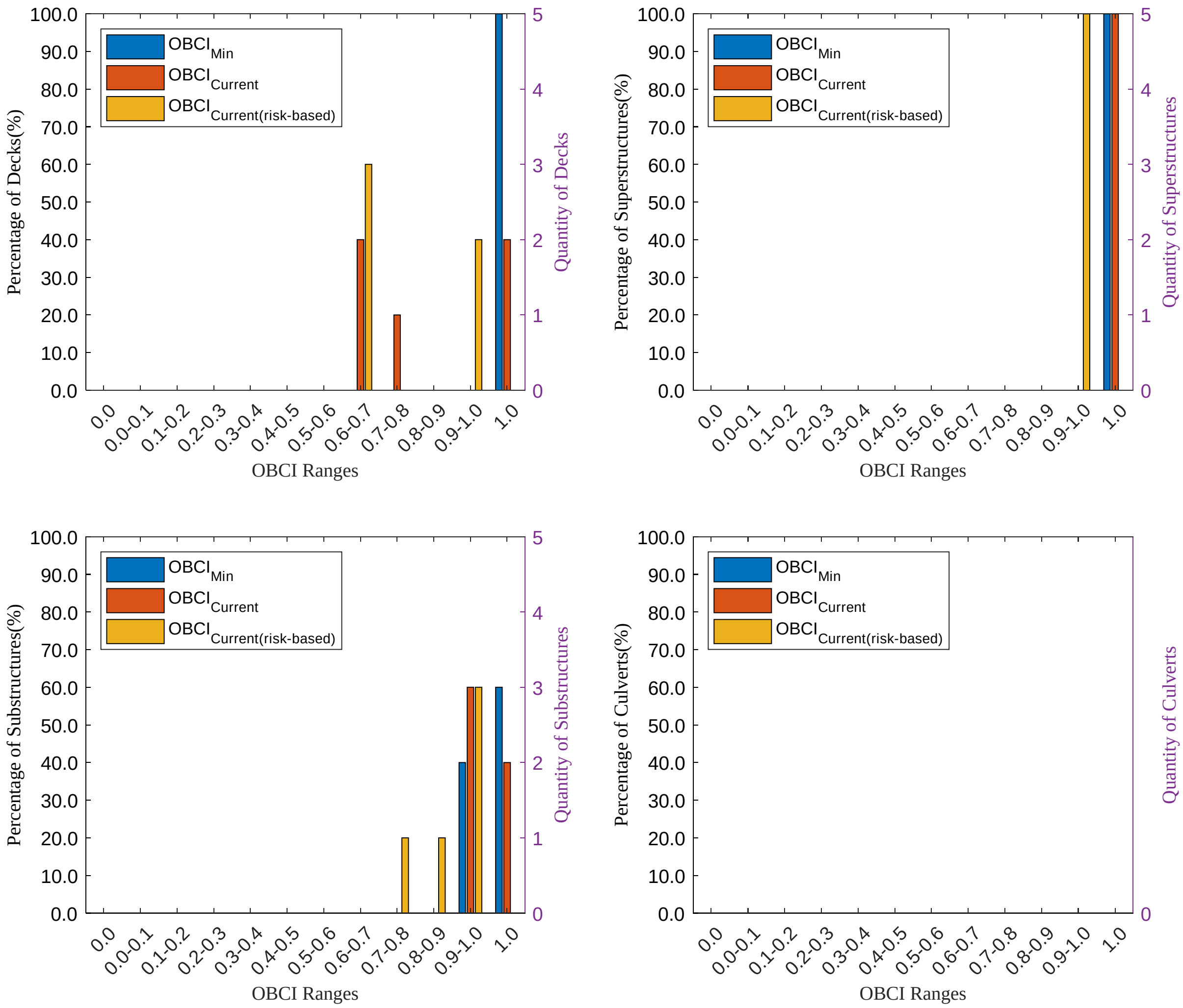
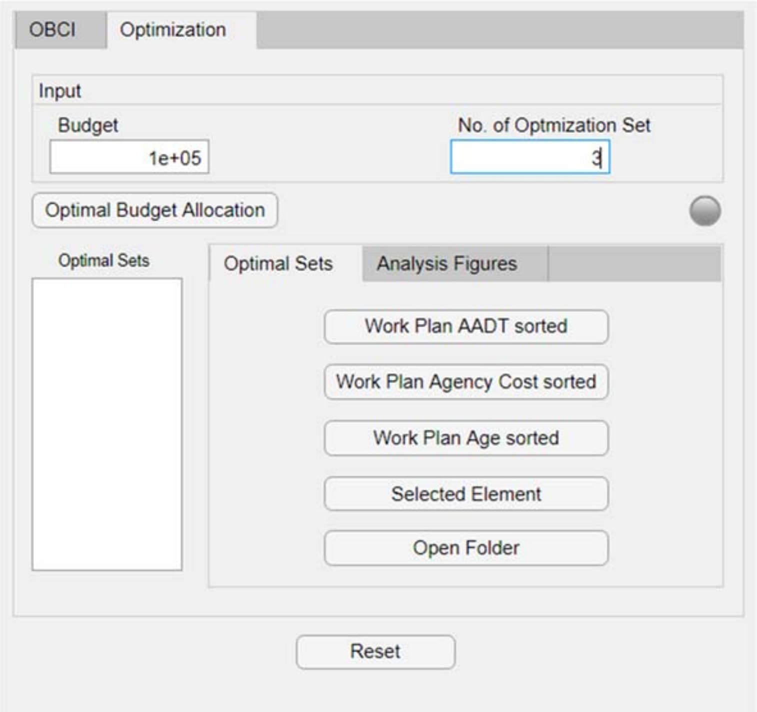


Figure D24- Percentage of components in various ranges of $OBCI_{min}$, $OBCI_{current}$, and $OBCI_{current(risk-based)}$

After the calculations for OBCI are finished, the program allows the user to perform optimal budget allocation in the ‘Optimization’ tab. The user can input the budget and the number of the optimization sets in the two edit fields of the input window as shown in Figure D25. After entering the values in the two edit fields, the user can click on the ‘Optimal Budget Allocation’ button to start the calculations of the optimization. Similar to the light in the ‘OBCI’ tab, the light next to the button shows the status of the calculation.

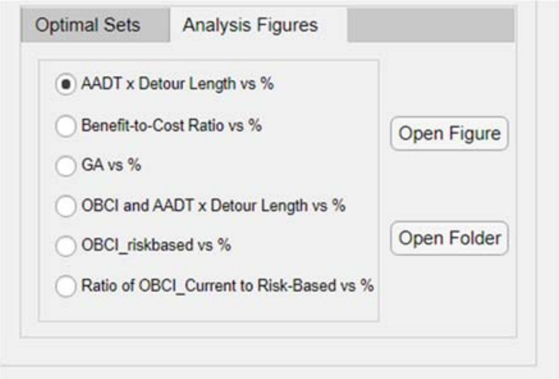


Budget: 1e+05

No. of Optmization Set: 3

Figure D25- Optimization tab

Once the calculations of the optimization are finished, all the optimal sets are displayed in the ‘Optimal Sets’ field. On the right side of the ‘Optimal Sets’ field, there are two tabs—‘Optimal Sets’ and ‘Analysis Figures’, whose functions are similar to their counterparts in ‘OBCI’ tab. The ‘Optimal Sets’ corresponds to the ‘OBCI results’ tab in the ‘OBCI’ tab. This tab is for generating all the excel output files, in which the buttons open excel files and the folder containing them. The ‘Analysis Figures’ tab in ‘Optimization’ corresponds to the ‘Analysis Figures’ tab in ‘OBCI’. It is for generating all the figure output files as shown in Figure D26.



● AADT x Detour Length vs %
○ Benefit-to-Cost Ratio vs %
○ GA vs %
○ OBCI and AADT x Detour Length vs %
○ OBCI_riskbased vs %
○ Ratio of OBCI_Current to Risk-Based vs %

Figure D26- Analysis Figures