RESEARCH & DEVELOPMENT

Guidelines for Prioritization of Bridge Replacement, Rehabilitation, and Preservation Projects

Matthew Whelan, PhD
Tara Cavalline, PhD, PE
Aidan Alar
Kelsey Lane
Department of Civil and Environmental Engineering
University of North Carolina at Charlotte

NCDOT Project 2016-05

FHWA/NC/2016-05

July 2019

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/NC/2016-05		

4. Title and Subtitle	5. Report Date
Guidelines for Prioritization of Bridge Replacement, Rehabilitation, and Preservation Projects	July 30, 2019
	6. Performing Organization Code
7. Author(s) Matthew J. Whelan, Tara L. Cavalline, Aidan Alar, Kelsey Lane	8. Performing Organization Report No.
9. Performing Organization Name and Address University of North Carolina at Charlotte 9201 University Blvd Charlotte, NC 28223-0001	10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Development Unit 104 Fayetteville Street Raleigh, North Carolina 27601	13. Type of Report and Period Covered Final Report August 1, 2015 – July 31, 2018 14. Sponsoring Agency Code RP 2016-05

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

Identification and prioritization of bridge replacement projects is one of the most critical aspects of an effective Bridge Management System. Currently, NCDOT uses a Priority Replacement Index that has developed as an ad-hoc ranking scale that lacks transparency between performance measures and priority and does not consistently reflect the preferences and priorities of NCDOT personnel that select bridge replacement projects. The objective of this research is revise the performance criteria and measures that are considered by the index and establish a transparent and objective relative weighting of measures for identification and prioritization of bridge replacement projects. Two practitioner surveys completed by Division Bridge Program Managers, Bridge Maintenance Engineers, and members of the Steering and Implementation Committee are used to address these objectives. Prioritization models derived from the survey responses as well as data-driven prioritization models developed through statistical regression are evaluated against asset management databases. The research identifies two alternatives to the PRI that improve the transparency of the index and incorporate a more comprehensive set of performance criteria and measures. One index is developed through binary logistic regression and provides a forecasted probability that a bridge will be selected for replacement. This binary logistic regression model produces a better distribution of scores for the bridges in the state inventory and results in fewer instances of bridges not scheduled for replacement receiving high priority for replacement. The second index is developed as a simple weighted average of all performance measures identified by the practitioner surveys as significant to the prioritization of bridge replacement projects. While the classification performance and distribution of scores is not as desirable as that produced by the binary logistic regression model, this index produces the most transparent link between performance measures and the priority score, with relative weighting of individual performance criteria that is reasonably consistent with the preference structure elicited from the practitioner surveys.

17. Key Words	18. Distribution Statement
Bridge replacement; prioritization; bridge management systems	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	200	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Disclaimer

Abbreviations

AASHTO	American Association of State Highway Transportation Offices
ADT	Average daily traffic
AHP	Analytical Hierarchy Process
BHI	Bridge health index
BL	Bridge length
BMS	Bridge Management System
Caltrans	California Department of Transportation
CEF	Cost effectiveness factor
CG	Capacity goal
CI	Consistency Index
CR	Consistency Ratio
DC	Deck Condition
DK	Deck rating
DL	Detour length
DOT	Department of Transportation
DTREE	Diagram tree
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
ft	Feet
GAO	Government Accountability Office
HI	Health index
in	Inches
INDOT	Indiana Department of Transportation
IRI	Pavement roughness
KPM	Key performance measures
LRS	Load rating score
m	Meters
MPOs	Metropolitan planning organization
MR&R	Maintenance, repair, and rehabilitation
MTKN	Midwestern Transportation Knowledge Network
NBI	National Bridge Inspection
NBIS	National Bridge Inspection Standards
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NCSU	North Carolina State University
ODOT	Ohio Department of Transportation
P5.0	Prioritization 5.0
PCI	Pavement condition index
PPN	Pavement priority number
PRI	Priority Replacement Index
RI	Random consistency index
RPOs	Rural transportation planning organization

SB	Substructure rating
SDDOT	South Dakota Department of Transportation
SHA	State Highway Agency
SHOPP	State Highway Operation Project Plan
SN_{40}	Pavement friction
SN_{efr}	Structure number
SP	Superstructure rating
SR	Sufficiency rating
STI	Strategic Transportation Investment
TIP	Transportation Improvement Program
US	United States
VP	Vertical roadway under / over clearance priority
VTrans	Vermont Agency of Transportation
WP	Clear bridge deck width priority

Acknowledgements

The research team would like to express gratitude to the North Carolina Department of Transportation for funding and providing technical support to this project. The Steering and Implementation Committee is acknowledged for providing invaluable technical oversight and direction throughout the research effort. In addition, this research would not have been possible without the participation of the Division Bridge Program Managers, Bridge Maintenance Engineers, and members of the Steering and Implementation Committee that completed the practitioner surveys. The research team also wants to acknowledge the timely support provided numerous times throughout the project by Mr. Foster Vestal to provide remote access to data within the NCDOT Bridge Management System and Bridge Inspection Reports.

Executive Summary

Identification and prioritization of bridge replacement projects is one of the most critical aspects of an effective Bridge Management System. Currently, NCDOT uses a ranking system referred to as the Priority Replacement Index, or PRI, which produces a score for each structure intended to reflect the relative priority for replacement of bridges based on their condition and design, use, functionality, and essentiality. This index has evolved over time as an ad-hoc collection of prior ranking formulae as well as directly incorporated performance measures. Review of the components of the PRI revealed the use of a large number of nonlinear and case-specific formula that obscure the transparency between the performance criteria and measures and the priority score. Additionally, the PRI was found to involve significant multiple counting of individual measures and lacked the ability to directly account for several factors associated with increased priority for replacement, namely maintenance-related considerations. Analysis of distributions of scores produced by the PRI as well as feedback from NCDOT Structures Management Unit personnel reveals that the ability of this index to clearly delineate bridges suitable for replacement from those unlikely to be selected for replacement is limited and the specific ranking of projects by the priority score does not consistently align with the projects identified by the personnel. Based on the current state of practice and the intent of recent legislative actions at the federal and state level, there is a need to revisit the performance criteria and measures utilized for prioritization of bridge replacement projects to develop an objective and transparent formula reflecting the relative importance of the goals and metrics valued by bridge engineers and planners. Furthermore, the approach for calculating a priority replacement score needs to be revised to eliminate multiple counting of performance measures, improve the classification accuracy to distinguish replacement projects from other bridges where rehabilitation may be a more suitable alternative, and enhance the ability of the index to correctly reflect the relative priority of individual replacement projects.

To address the research needs, an initial practitioner survey was developed to identify performance criteria and associated measures that are currently considered by NCDOT Division Bridge Program Managers when selecting and ranking potential bridge replacement projects. The responses obtained from this first survey favored many of the conventional performance measures utilized in the PRI and Sufficiency Rating and eliminated many of the performance criteria and measures utilized by NCDOT within the Strategic Mobility Formula used to prioritize other transportation projects in the State Transportation Improvement Program. In addition, the survey revealed a need to introduce new performance criteria and measures to incorporate the extent and urgency of current maintenance needs identified for each structure through element level inspections as well as consider the effects of recently performance maintenance actions on the priority for bridge replacement. To address these needs, new performance measures quantifying current maintenance needs and historical maintenance burden were developed through data-driven analysis linking the Maintenance Management System (MMS), element level inspection summaries, and BMS databases. A second practitioner survey was completed by a larger set of respondents to produce relative weights for each of the performance criteria and measures through methodologies recommended within the NCHRP Report 590 guidance. Following the principles

of decision analysis, value functions were developed for the final set of performance measures and criteria through statistical analysis of bridge characteristics across the entire state inventory. Both linear value functions proposed in the literature as well as value functions developed using empirical cumulative distribution functions, which are consistent with the current state of practice used within the Prioritization 5.0 framework, were developed and evaluated in this study. In addition to eliciting practitioner preferences and risk attitudes through surveying techniques, statistical regressions were performed on a unique database assembled from the BMS, MMS, element level inspection data, and lists of active and scheduled bridge replacement projects to arrive at alternative prioritization formulae that optimize the predictive ability to classify bridge replacement projects. Both the models developed through the practitioner surveys and those developed through statistical regression were evaluated by comparing their predictions to the replacement status of bridges currently in the state inventory.

The research produces recommendations for future calculation of replacement priority within the BMS. Statistical measures were used to assess the classification performance of each index quantitatively, while qualitative assessments of the distributions of scores and positive predictive value were used to identify the approaches that best distinguish replacement projects. From a pure classification perspective, the PRI was found to result in slightly improved classification accuracy compared to the models developed from the practitioner surveys and the models developed through each statistical regression technique. However, classification accuracy does not guarantee suitable score distribution or relative ranking of replacement projects. The PRI also suffers from multiple counting of performance measures, incomplete consideration of all factors known to influence the decision-making process, and a lack of clear transparency between the performance measures and the priority score. Through statistical inference, two alternatives to the PRI were identified that improve the transparency of the index and incorporate a more comprehensive set of performance criteria and measures. One index was developed through binary logistic regression and provides a forecasted probability that a bridge will be selected for replacement. This binary logistic regression model produces a better distribution of scores for the bridges in the state inventory and results in fewer instances of bridges not scheduled for replacement receiving a score implying a high priority for replacement. This model may also facilitate the introduction of probabilistic strategies for network-level analysis in the BMS and complement the use of probabilistic deterioration models developed in prior research. The second index was developed as a simple weighted average of all performance measures identified by the practitioner surveys as significant to the prioritization of bridge replacement projects. While the classification performance and distribution of scores is not as desirable as that produced by the binary logistic regression model, this index produces the most transparent link between performance measures and the priority score. The statistical models are generally consistent with the preference structure elicited from the practitioner surveys, although some differences in relative weighting of individual performance criteria and measures was observed.

The developed prioritization guidelines and methods sought through this research are not intended to replace the decision-making process that involves direct coordination with Division Bridge Program Managers and Bridge Maintenance Engineers to select bridge replacement projects. The performance measures adopted in this research are limited by the descriptive granularity of the data in the BMS and MMS, which often does not accurately capture with sufficient detail the condition, history, and other factors specific to each bridge to permit reliable distinction and ranking of individual bridge projects. Likewise, site-specific conditions that are not easily captured by data in the BMS or MMS records can lead to cases where rehabilitation strategies are cost-prohibitive and replacement is the only option on bridges that may otherwise obtain a low prioritization score. The indices developed and recommended for use can at best be used to provide a means for producing informed simulations within the BMS to forecast future needs and to assist in producing a list of potential bridge replacement projects requiring subsequent manual review by decision-makers.

Table of Contents

1. Introduction

State highway agencies (SHA) are tasked with maintaining, repairing, and replacing bridges to support the travelling public. These agencies need to develop programs that prioritize candidate projects in a manner that ensures that bridges are selected for maintenance, repair, and replacement at appropriate times and within budgetary constraints. To accomplish this, prioritization methods must be developed that utilize and appropriately weigh the desired measures and agency preferences to identify candidate bridges that, if selected, help a SHA achieve performance criteria. Federal and state legislation provide guidance for national and statewide goals for transportation improvements, while each SHA is tasked with establishing prioritization indexes to measure progress towards those goals in a manner that reflects agency preferences and risk attitudes.

Prioritization methods provide a framework for a SHA to select bridges for MR&R and replacement. Means of identifying, organizing, and weighting criteria important to an agency can utilize concepts from conventional decision analysis. Decision analysis is the process of arranging criteria in order of preference to select the best candidate. Sometimes, decision analysis can be easily implemented, for example when the preferred order is based purely on cost. Other times, the situation is more complex and multiple factors (such as cost, safety, impact to the traveling public, and risk) affect the ranking. Conflicting criteria can also be an issue. Decision makers are often faced with the process of value trade-off, which is when a choice must be made between the benefits derived from one criterion relative to another (Patidar et al. 2007).

To develop prioritization strategies, sets of performance criteria deemed important to the stakeholders and performance measures designed to quantify the significance or opportunities offered by specific decisions or projects to these performance criteria must be identified. Performance criteria, which are referred to (somewhat interchangeably) as “goals” or “criteria” throughout literature, define the alternative actions and trade-offs within a decision. Performance measures are used to assess progress towards meeting the performance criteria. A performance measure is the quantitative or qualitative impact of a specific physical action or policy that reflects a concern of the policy maker, user, or community (Patidar et al. 2007). Performance measures should satisfy the following criteria (Keeny and Raiffa 1976):

- completeness, covering all of the important aspects of the problem
- operativeness, being readily calculated from available data
- non-redundancy, avoiding double counting, and
- minimalness, keeping the size of the problem dimensions as small as possible.

Measures of the relative importance of project attributes and impacts should also be considered, along with the risk attitudes of the stakeholders. Additionally, the ranking or scoring system used in the prioritization methodology should suitably scale the results to allow a clear identification of candidate bridges through an appropriate spread in ranking. Ultimately, a prioritization index should provide a SHA with the ability to understand the implication of specific factors in the rankings and produce suitable resolution to facilitate consideration of multiple alternatives for implementation.

1.1 Priority Replacement Index (PRI)

Currently, NCDOT uses a ranking system referred to as the Priority Replacement Index (PRI) that produces a score for each structure that is intended to reflect the relative priority for replacement of bridges based on their condition and design, use, and functionality data. The PRI ranking system uses a combination of two previously used prioritization formulas, the FHWA Sufficiency Rating and Deficiency Points, in conjunction with additional bridge infrastructure measures. The performance measures that are used for calculating the PRI are nationally utilized metrics that are indexed in the National Bridge Inventory (NBI) (Weseman, 1995). The current PRI is computed on a 120 point scale, where the higher the number of points a bridge is assigned on the scale, the more likely that the given bridge is a good candidate for replacement. The PRI equation is shown as (1.1):

$$\begin{aligned} PRI = {} & 0.45(\text{Deficiency Points}) + 0.45(100 - \text{Sufficiency Rating}) + 1.25[28 - \text{Deck Condition} \\ & - \text{Superstructure Condition} - 2(\text{Substructure Condition})] + 10(\text{Temporary Shoring}) \end{aligned} \tag{1.1}$$

Ideally, the PRI ranking is intended to serve as an objective and actionable method for clearly distinguishing bridges requiring replacement rather than repair or rehabilitation and sorting the projects in order of priority. While there are no fixed thresholds used to identify replacement candidates, a general guideline has been suggested to separate the PRI scale into three ranges for replacement. Under this guideline, bridges with a PRI score from zero up to 30 are considered "poor candidates" for replacements, bridges with a score of 30 up to 50 are considered "good" candidates, and bridges with a score of 50 or higher are considered "very good" candidates for replacement.

Developed in the early 1980s, the Deficiency Points index was designed to quantify the likelihood and urgency for a bridge replacement with higher point totals being associated with greater priority (Johnston and Zia, 1984). Four main performance criteria are addressed in the Deficiency Points calculation: single vehicle load capacity, vertical roadway under/over clearances, estimated remaining life, and clear deck width. The performance criteria in the Deficiency Points calculation focus heavily on vehicle to bridge posting weight ratios, functionality appraisal ratings, geometry, Average Daily Traffic (ADT), and estimated remaining life.

The Sufficiency Rating is a federal rating that was previously used to determine eligibility for federal funding to repair or replace each bridge (FHWA, 1995). It is an overall rating of structural adequacy, functionality, and essentiality of use and is computed on a 100 point scale. Since this rating evaluates sufficiency rather than deficiency, bridges with lower Sufficiency Ratings are often considered to be more suitable candidates for replacement. The Sufficiency Rating is based upon four performance criteria: structural adequacy and safety, serviceability and functional obsolescence, essentiality for public use, and special reductions. The performance criteria are calculated through a number of both linear and nonlinear equations that utilize 19 different performance measures sourced from the NBI data. Further information on the Sufficiency Rating can be found in the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (FHWA, 1995). The remaining components of the PRI are general condition ratings (deck, superstructure, and substructure) and an additional binary assignment of points that are incorporated if the structure has been provided with temporary shoring.

Currently, the NCDOT AgileAssets BMS does not directly identify replacement projects based on the PRI, and according to NCDOT SMU personnel, the PRI does not consistently produce desirable outcomes. Specifically, candidate projects sorted by PRI do not align with the prioritization of projects identified by personnel. A main desire for the new index would be to compile a candidate list that is a closer reflection of the projects selected by Division Engineers, who are more familiar with local conditions of bridges within the area they support, and other agency goals. Also, the new formula should consider if and how priorities and risk attitudes in the decision-making process change based on the location of a bridge within the state (i.e. the Coastal, Piedmont, and Mountain geographical region). NCDOT personnel were also not satisfied with the correlation of Deficiency Points scoring to the PRI.

Performance measures in the PRI encompass a broad range of bridge characteristics, and the impact of some of these characteristics on the PRI scoring is not readily evident due to the complexity of the functions incorporated within the PRI. Double-counting (or triple or quadruple-counting) exists, as well as underrepresentation of factors of importance to NCDOT and over-represented metrics that skew the index. Early in this study, an analysis was performed to investigate if the PRI is in fact a poor indicator for bridge replacement projects by evaluating the PRI scores of bridges that have been selected for replacement relative to the remaining bridges in the state inventory that are not scheduled to be replaced. This was based on bridge data sourced from the 2016 Network Master database along with a list of all bridges either currently being replaced or scheduled for replacement that was provided by the NCDOT. This analysis consisted of records for 13,826 bridges of which 1,249 or 9.03% were currently scheduled for replacement. The distributions of PRI scores among bridges selected for replacement and those not selected for replacement were used to evaluate the performance of the PRI as a means of classifying bridge replacement projects and to postulate reasons for shortcomings in the performance of the index.

The histograms of PRI scores for bridges that are selected for replacement and those not currently selected for replacement are shown in Figure 1.2a and Figure 1.2b, respectively. On average, bridges selected for replacement do tend to have higher PRI scores than those not selected for replacement, however a closer examination of the data reveals issues within the index. First, the histograms reveal that bridges selected for replacement exhibit a bimodal distribution of scores that has mean and median values in the lower half of the index range and a spread that encompasses a large portion of the index range. Ideally, a prioritization index should skew scores for bridges not suitable for replacement toward zero, while distributing the scores for bridges prioritized for replacement across the range of the index with a good spread that does not result in clustering and produces minimal overlap with the scores assigned to bridges that are not selected for replacement.

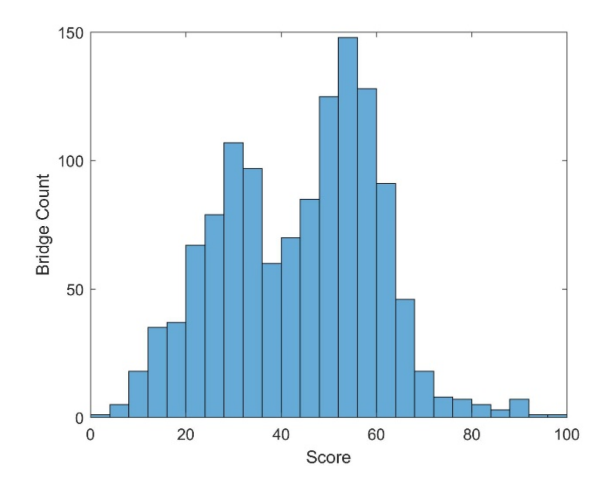


Figure 1.2a: Histogram of PRI Scores for Bridges Selected for Replacement

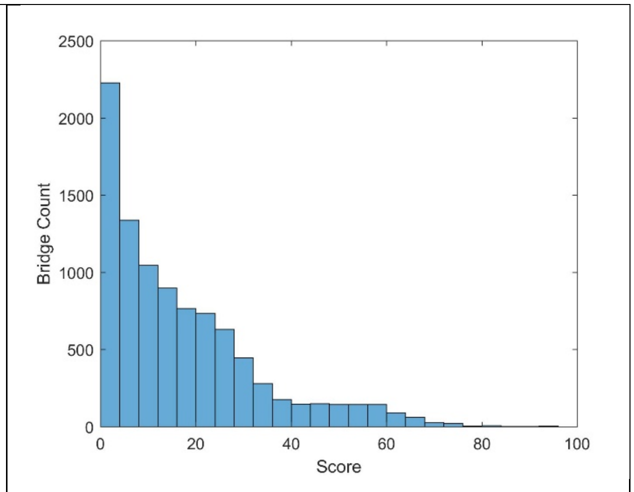


Figure 1.2b: Histogram of PRI Scores for Bridges Not Selected for Replacement

An analysis of the PRI score at the extents of the distributions reveals that only two of the bridges within the ten highest PRI scores are currently selected for replacement, as shown in Figure 1.3. This analysis also reveals that the PRI does not utilize the full 120 point range when implemented in practice and that the majority of bridges are clustered at PRI scores below 30. While this would be acceptable if this skew was simply the result of proper classification of bridges not requiring replacement (which is the majority of bridges in the state) as low PRI structures, a comparative analysis of the number of bridges within the recommended ranges for qualitative classification of projects (Table 1.4) reveals classification issues. As evidenced by Table 1.4, there are more bridges that are not currently selected for replacement than those selected for replacement in both of the PRI ranges associated with "Very Good" and "Good" candidates. Collectively, this analysis supports the conclusion developed by NCDOT engineers that the PRI is an imperfect index for classification and prioritization of bridge replacement projects with numerous shortcomings.

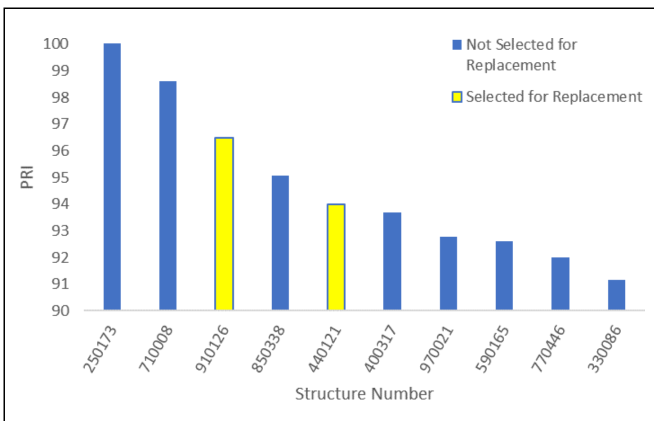


Figure 1.3: Classification of Bridges with the Ten Highest PRI Values Currently in the State Inventory

Table 1.4: Comparison of the Number of Currently Selected and Not Selected Bridge Replacement Projects by PRI Range

Replacement Candidacy	**PRI Range**	**Selected**	**Not Selected**
Very Good	PRI ≥ 50	537	588
Good	30 ≤ PRI < 50	409	1023
Poor	PRI < 30	303	10966

One suspected reason for the apparent shortcomings in the PRI is that it was developed as an ad-hoc index collecting several prior indices that were not originally designed to be utilized jointly. As a result, the PRI suffers from significant multiple-counting of performance measures and does not present a clearly transparent view of how performance measures are individually weighted in computing the priority score. A count of the number of uses of each of the performance measures and the maximum potential contribution to the PRI by each measure was performed to illustrate these issues in the current index. Out of the 21 performance measures that are used for calculating the current PRI, seven suffer from either double, triple, or quadruple counting, as shown in Table 1.5.

An analysis of the maximum potential number of points that each performance measure can contribute to the PRI is presented in Figure 1.4, which is adapted from one of the two Master of Science theses developed from this research effort (Lane, 2016). Since several equations in the PRI are either conditional or nonlinear, the actual contribution of each measure to the index is dependent on the individual bridge characteristics (which may be viewed as another shortcoming of the index). The analysis reveals that the ADT carried by the bridge has the largest potential impact on the PRI score by affecting as many as 72.62 points, while the Defense Highway Designation has the smallest potential effect with only a maximum effect on 1.76 points. Overall, this analysis indicates that the PRI score is dominated by the ADT and general condition ratings, while a large number of the 21 performance measures have relatively little impact on the PRI score.

Table 1.5: Multiple-Counted NBI Performance Measures in the PRI

NBI Item	Performance Measure	Count
29	ADT Over	4
19	Detour Length	3
51	Clear Deck Width	2
53	Vertical Clearance Over	2
58	Deck Condition	2
60	Substructure Rating	2
59	Superstructure Rating	2

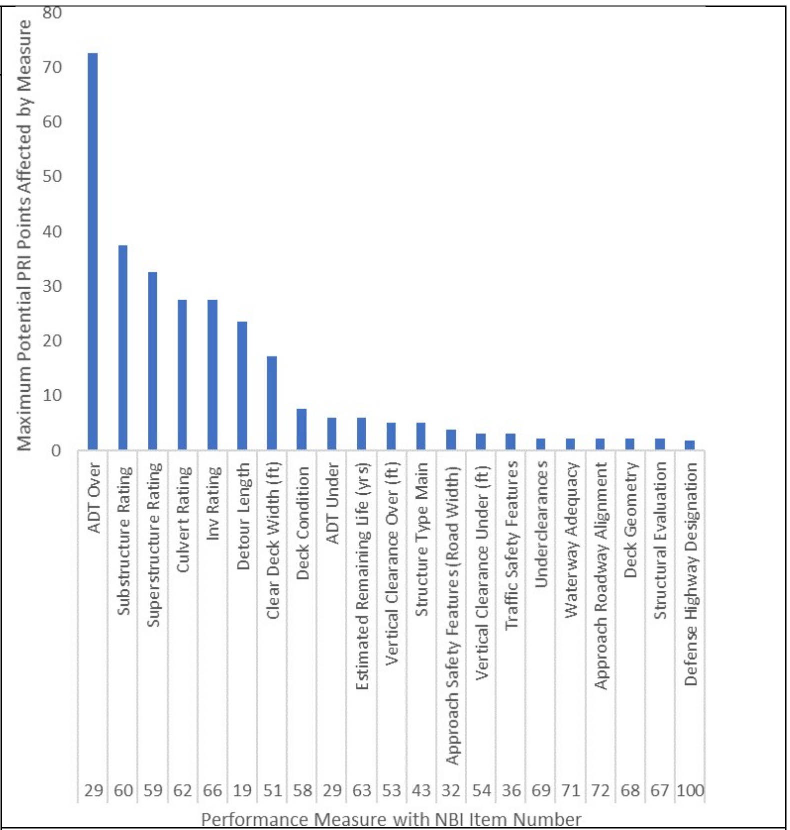


Figure 1.4: Maximum Point Effect of Performance Measures in the PRI

In addition to double counting of performance measures, another potential reason for the shortcomings of the PRI is that this ranking system incorporates general condition ratings rather than element-level inspection data. General condition ratings aggregate the inspector ratings to form a single condition rating for each primary component of the bridge, but do not offer the same granularity of information on the location and extent of structural deterioration that element-level ratings do. Inspection and rating of bridges at the element-level has been mandated by the FHWA as part of the MAP-21 legislation (MAP-21, 2012). A report on the improvements to bridge inspections nationally showed that the NBI served as the main reporting system but did not include condition ratings that are granular enough for maintenance prioritization (Sobanjo and Thompson, 2016). The PRI only has three condition ratings that address the overall state of large parts of a bridge and do not give inspectors the ability to record localized deterioration across the elements of the structure and substructure of a bridge.

Since 2014, NCDOT bridge inspectors have recorded element-level health ratings for each bridge to stay compliant with the FHWA inspection and recording requirements (Farrar and Newton, 2014). Furthermore, using the element-level health ratings, a list of inspector recommended maintenance needs is developed for each structure. These tasks range from insignificant actions, such as removing deck debris and maintaining handrails, to major rehabilitation, such as replacing timber piles and repairing modular bridge joints. Ideally, a bridge with low maintenance needs should be considered a candidate for repair or rehabilitation instead of replacement. NCDOT has recently introduced the storage of new element-level condition rating data in their BMS as well as integrated the database of Inspector Recommended Maintenance Needs required to correct low element condition ratings for each structure. In this database, the element-level condition ratings for each structure are associated with specific maintenance actions for repair of each element and aggregated into total counts. Based on the condition rating of the elements, the corrective actions and counts are designated as either priority maintenance needs or recommended maintenance needs. Collectively this information allows for more detailed accounting of the type and number of elements requiring corrective action than the general condition ratings do and, further, provides a means for estimating the total cost of repairs.

A third shortcoming of the current PRI is that it does not consider the effects of maintenance history on the decision to prioritize replacement of a structure. Maintenance history is defined in this study as the maintenance actions that have been completed on each bridge and their associated costs. Maintenance history is likely to influence prioritization of bridge replacements in two ways. First, if the condition and rate of deterioration of a bridge has caused NCDOT to repeatedly perform maintenance year after year on the structure to maintain an acceptable level of service, then it is more likely to be a candidate for replacement. Such bridges present a maintenance burden that requires above average use of state resources and the cost-benefit ratio for such burdensome maintenance is unlikely to be a better economic decision than replacement. In contrast, bridges that have recently received either major investments in rehabilitation or preservation actions are less likely to be priority candidates for replacement, as returns on these investments in terms of increased service life are expected.

For a period of approximately ten years, NCDOT engineers have maintained a digital record of the number of maintenance actions performed on each bridge as well as the cost of each action. There are 12,299 bridges in North Carolina with recorded maintenance history that occurred within the past ten years. The average number of actions per bridge is 4.78 actions over ten years with a standard deviation of 4.51 actions. Overall, there are 58,832 recorded actions that were performed in the past ten years at an average of 5,454 actions per year. However, this maintenance history is not explicitly incorporated in the PRI or implicitly captured by any of the performance measures currently incorporated in the index.

1.2 NCDOT Research Needs

Particularly in light of the structure of the overarching Transportation Investment Strategy Formula and the transparent reporting requirements of the law, the SMU needs to review previous and current practices used for indexing bridges for replacement, rehabilitation, and preservation to devise an appropriate index consistent with the intent of the current law. Regardless of the recent changes in State law, prioritization of bridge projects is one of the most critical aspects of an effective Bridge Management System and research to improve the current indices used to better balance agency preferences, network needs, and risk tolerances can result in optimization of the significant portion of the NCDOT annual budget allocated to bridge replacement and preservation. Furthermore, the methodology established through the proposed research could be extended to additional components of the Asset Management System to maximize the impact of the research results and investment.

Based on the current state of practice as well as implications of the Strategic Transportation Investments prioritization funding plan, the needs of the Structures Management Unit are as follows:

- Objective and transparent performance metrics need to be revisited and reformulated to address any criteria from the new legislation, such as benefit-cost, traffic safety, network vulnerability, condition, and congestion, that are deemed to be important to the prioritization of bridge replacement projects. Value functions that define a mathematical formula for translating performance measures to quantitative indices appropriate for a composite prioritization index will need to be devised for these reformulated metrics.
- Since prioritization indices combine individual value functions developed from performance metrics, the relative weighting, scaling, and amalgamation strategies appropriate for Statewide Strategic Mobility, Regional Impact, and Division Needs projects need to be formulated to develop objective performance indices. Specifically, the composite indices need to 1) reflect relative importance and acceptable risk criteria, as valued by the bridge engineer and planner; and 2) produce a wide spread across the index that clearly distinguishes priority amongst potential projects while minimizing double-counting of performance measures.
- While prioritization of bridge replacement projects is the primary emphasis and need addressed in the proposed project, the prioritization of bridge rehabilitation and preservation projects, as well as culvert replacement projects, is an additional need that can potentially be addressed concurrently or subsequently to the proposed research.

2. Result of Literature Review

Note: A summary of key literature findings is presented in this section. The full literature review supporting this work, along with a complete list of references, is provided in Appendix A of this report.

2.1 Bridge Project Prioritization in North Carolina and Recent Legislation

Over the past several decades, the North Carolina Department of Transportation (NCDOT) has utilized various methods to guide bridge project prioritization and selection. The method used prior to 1990 was simply preparation of a list of possible bridge candidates, developed by NCDOT personnel, which was distributed among division bridge supervisors (Garrett, 2012). In 2012, the Federal Highway Administration (FHWA) established MAP-21 legislation that provides a new framework for US transportation policy and funding allocation. Although MAP-21 provides flexibility for states to identify and select candidate projects, it does mandate performance measurement and transparency in the allocation of funding to ensure accountability to the public. One of the primary performance-based planning aspects of MAP-21 is a set of seven thematic performance criteria areas: safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays. States are tasked with developing measures and targets towards these seven performance criteria that can be utilized to demonstrate progress concerning transportation improvements that address the national goals (FHWA, 2012).

The PRI is a multi-criteria formula that is currently used by NCDOT to provide a score based on condition and functional data in the Bridge Management System (BMS) for each of the highway bridges in North Carolina to aid in ranking the priority of potential replacement projects. The PRI comprehensively utilizes many of the performance measures considered to be important by the NCDOT SMU. However, anecdotal evidence from SMU personnel, supported by an analysis of PRI score distributions among bridges selected and not selected for replacement (presented in Section 1.1) has suggested that the PRI is a poor indicator of whether a bridge will actually be scheduled for replacement. In addition, the PRI double counts some performance measures, uses nonlinear and case-based formulas that do not produce a transparent link between measures and priority, and neglects some important maintenance related considerations that influence priority for replacement.

The Strategic Transportation Investments Law (House Bill 817) signed by Governor McCrory in June 2013 established a strategic prioritization funding plan for the State's transportation resources that mandates an investment formula with an objective ranking framework to prioritize and justify construction, maintenance, and preservation projects (Figure 2.1). A clear objective of the ratified law is transparency, as evidenced by the requirement that the Department of Transportation publish the quantitative criteria and associated scoring methodologies for each category of project, qualitative metrics used by each region or division to generate local input from Metropolitan Planning Organization (MPO) and Rural Transportation Planning Organization (RPO), and all formulas used to obtain project rankings in each category.

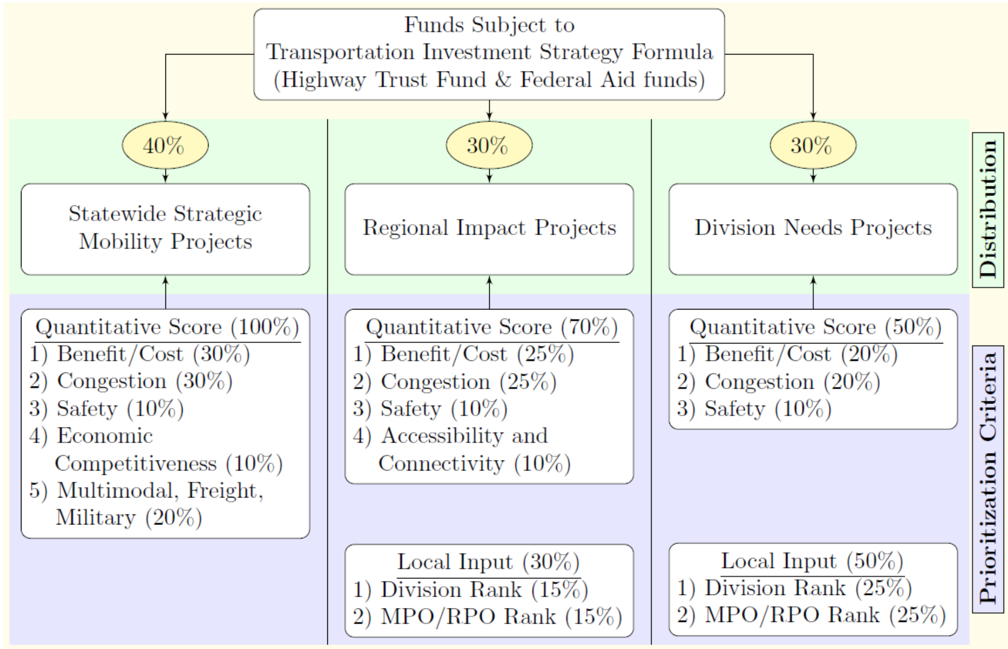


Figure 2.1. Overview of Strategic Mobility Formula with November 7, 2013 criteria proposed by Board of Transportation for Highway projects (Note: the formula has since been revised)

The ratified Strategic Transportation Investments Law stipulates that bridge replacement, interstate maintenance, and highway safety improvement projects are also subject to the same investment formula as other transportation projects in the State. However, section 136-189.11(c) of the law excludes these specific projects from the prioritization criteria used to rank projects within the categories of Strategic Mobility, Regional Impact, and Division Need. Despite this exclusion, it is important that the NCDOT implements an objective and transparent prioritization index that can be justified by criteria similar to those required for other transportation projects. The need for effective and transparent prioritization of bridge replacement, preservation, and rehabilitation projects continues to increase in urgency. Specifically, recent NCDOT analysis of State Transportation Infrastructure Program (STIP) funding indicated that only about 30% of structurally deficient bridges are scheduled for replacement, while the need for increased resources to replace and maintain the increasing population of aged structures is expanding.

NCDOT utilizes the project prioritization schemes outlined in Prioritization 5.0 (or P5.0) to allocate funds for transportation projects subject to the STI (NCDOT, 2018). Designed to meet the requirements of North Carolina’s STI legislation, P5.0 was developed by a Prioritization Workgroup of metropolitan planning organizations (MPOs), rural transportation planning organizations (RPOs), division engineers, and local government advocacy groups. The STI legislation provides a funding formula for all capital expenditures, which draw from the NC Highway Trust Fund, and is designed to fund the “best” transportation projects regardless of mode (NCDOT, 2018). P5.0 provides a framework for funding allocation for highway, non-highway, aviation, bicycle/pedestrian, ferry, and rail mobility projects.

The P5.0 Highway Criteria incorporates ten performance criteria, each defined with one or more performance measures (Table 2.1). Each performance criterion is weighted based on the funding category, which uses both quantitative data, performance measures, and local input. The performance criteria are aspects related to highway infrastructure based not only on condition, but how it impacts the community in which it is located. Division and local input, as well as MPO/RPO input are also included in the total score, as shown in Table 2.2.

Table 2.1: NCDOT P5.0 highway performance measure weighting (NCDOT, 2018)

Performance Criteria	Performance Criteria Weight	Performance Measure	Measure Weight
Congestion	30%	Existing Volume / Capacity Ratio	60% (Statewide)
			80% (Regional)
			100% (Division)
		Existing Volume	40% (Statewide)
			20% (Regional)
			0% (Division)
Benefit-Cost	25%	Benefit-Cost	25%
Freight	25%	Truck Volume	50%
		Volume / Capacity	30%
		Distance to Freight Terminal	20%
Safety	10%	Crash Density	20%
		Crash Severity	20%
		Critical Crash Rate	20%
		Safety Benefits	40%
Economic Competitiveness	10%	% Change in County Economy	50%
		Change in Jobs	50%

Table 2.2: NCDOT P5.0 Highway criteria and weights (NCDOT, 2018)

Funding Category	Quantitative Data	Local Input	
		Division Rank	MPO/RPO Rank
Statewide Mobility	Congestion = 30% Benefit-Cost = 25% Freight = 25% Safety = 10% Economic Competitiveness = 15%	--	--
	Total = 100%		
Regional Impact	Congestion = 20% Benefit-Cost = 20% Safety = 10% Accessibility / Connectivity = 10% Freight = 10%	15%	15%
	Total = 70%		
Division Needs	Congestion = 15% Benefit-Cost = 15% Safety = 10% Accessibility / Connectivity = 5% Freight = 5%	25%	25%
	Total = 50%		

Depending on the funding category, each performance criterion is incorporated into the prioritization formula and the appropriate weights for each criterion are applied. Region A and Divisions 1, 5, 6, 7, 8, 11, and 13 utilize area-specific criteria weights for regional impact and division needs scoring, including weight additions and reductions for area-specific priorities, such as those listed previously, or additional priorities such as pavement condition (NCDOT, 2018). These are shown in Table 2.3.

Table 2.3. NCDOT P5.0 Area-specific Criteria Weights

Location	Weight Reductions	Weight Additions
Region A	-5% Congestion	+5% Freight
Division 1	-5% Freight -10% Benefit/Cost -10% Congestion	+10% Safety +15% Accessibility/Connectivity
Division 5	-5% Freight -5% Accessibility/Connectivity	+5% Benefit/Cost +5% Safety
Divisions 6, 7, 8, 11	-5% Freight	+5% Safety
Division 13	-5% Accessibility/Connectivity	+5% Safety
Division 14	-5% Freight -5% Accessibility/Connectivity	+10% Pavement Condition

2.2 Guidelines for Objective Decision-Making and Practices Used in Other States

Most modern bridge prioritization programs are founded within principles of Performance-Based Resource Allocation (PBRA), which is a decision-making framework that objectively selects actions based on defined agency or policy goals using quantitative measures of performance. NCHRP Report 590 provides one of the most comprehensive reviews on decision theory techniques recommended for prioritizing projects within a Bridge Management System using multi-objective and multi-constraint optimization, such as AgileAssets (Patidar et al. 2007). Within an optimization framework, selection of the optimal combination of bridge projects for any given year is done to maximize the "utility" of the selected projects, under the given budgetary and non-budgetary constraints provided. In most, if not all, instances, the measure of utility is developed from performance measures, which quantify the impact of the project on such metrics as bridge health, traffic congestion, network vulnerability, safety, and many other indicators that are reflected in the current legislation. However, the construction of the utility function should not be performed simply as the sum of individual performance measures, since this fails to capture relative importance and risk. Instead, utility of a bridge replacement, rehabilitation, or preservation project reflects the priority associated with the project by aggregating "value functions" that scale performance measures based on decision maker preferences and also incorporating weighting factors and functions that express decision maker attitudes on importance and risk aversion. In both cases, since the value functions reflect decision maker preferences and the utility functions reflect the decision maker outlook on importance and risk, these functions are best obtained through statistical regression of preference surveys to illicit these preference structures from the decision makers. A more complete discussion on value and utility functions is presented in Section A.5.2 of Appendix A.

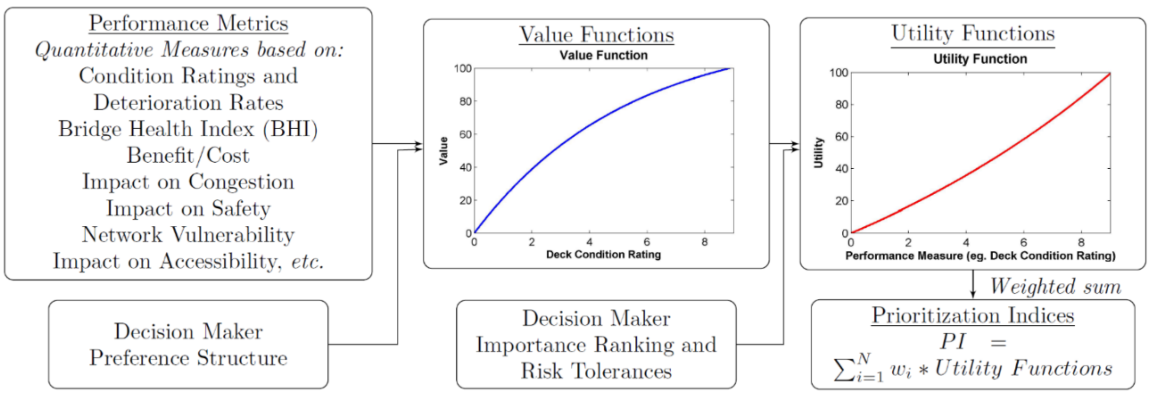


Figure 2.2. General NCHRP Recommended Decision Theory Framework for Development of Prioritization Indices from Performance Measures

While the decision theory framework for bridge prioritization is mature and scientifically grounded, it is clear in the current literature that the application requires a significant research effort to tailor the process to the preferences, goals/needs, and attitudes of individual state transportation departments. In fact, the entire framework presents application-specific challenges, originating with the selection of performance measures to properly express agency goals and legislative mandates without double-counting variables, and extending to the development of a composite prioritization index that effectively spreads project rankings over a sufficient scale to clearly distinguish projects with top priority from the remainder of eligible projects. Ideally, the developed indices for prioritization should be validated and, if necessary, empirically calibrated to the actual bridge inventory database for the current record year to ensure the ability of the indices to distinguish priority projects, while still properly reflecting the importance and risk preferences of the decision makers.

A number of states and cities have implemented legislation requiring transportation project prioritization processes for improvement of the cost-effectiveness of allocated funds as well as public transparency. Although each state has a particular approach to bridge project prioritizations, methods vary based on states preferences, BMS capabilities, and other factors. Some have devised a mixed quantitative/qualitative ranking system that incorporates traditional engineering measures around sufficiency ratings, cost-benefit analysis, vulnerabilities, and usage with input from regional planning commissions. However, most use quantitative rankings formulated from performance metrics developed around accessible data from NBI records, traffic data, maintenance histories, or other databases. Identification of performance goals (also called performance criteria or attributes) and measures that reflect SHA preferences, while addressing legislative requirements when appropriate, is inherently an initial step in improving prioritization approaches.

As part of this work, a scan of relevant published literature and agency websites was conducted to prepare a summary of selected states' identification of performance goals and measures, as well as approaches to developing a prioritization index. A comprehensive discussion of these findings is presented in the full literature review in Appendix A of this report, and a summary is presented in the following paragraphs.

NCHRP Report 590 does not prescribe specific goals and measures to be utilized, but does list several general goals for the purposes of providing guidance throughout the report. These include (Patidar et al. 2007):

Preservation of bridge condition

- Traffic safety enhancement
- Protection from extreme events
- Agency cost minimization
- User cost minimization

Performance goals and measures utilized by NCDOT P5.0 for highway projects are summarized in Table 2.1 and 2.2. More broadly, performance goals and can often be generalized into the categories shown in Table 2.5. Also included in Table 2.5 are typical performance measures utilized by North Carolina and other states in evaluating project need and establishing priorities. Within each performance measure, the approach to compute the score can be one commonly utilized, such as use of the Sufficiency Rating (as computed by FHWA, 1995), or another characteristic recorded in the database, such as ADT, vertical clearance, or detour length. Alternatively, the approach to computing the score can be adjusted to suit agency preferences using weighting, scaling, and other means.

Table 2.5: Summary of general performance goals and typically utilized measures

Performance Goal	Typical Performance Measure	Agency using (or recommending) performance goal and source literature
Infrastructure Condition	• Sufficiency Rating • Deck condition • Superstructure condition • Substructure condition • Posting • Fracture critical • Scour critical	• NCHRP Report 590 (Patidar et al., 2007) • Federal Highway Administration (FHWA, 1995) • Indiana DOT (Sinha et al., 2009) • South Dakota DOT (SDDOT, 2016) • Ohio DOT (ODOT, 2003) • CalTrans (Shepard and Johnson, 2001; Johnson, 2008) • North Carolina DOT (NCDOT, 2018)
Benefit-Cost	• User impact (traffic delays, detour length) • Agency cost • Additional funding available (tolls, local funds)	• NCHRP Report 590 (Patidar et al., 2007) • Indiana DOT (Sinha et al., 2009) • Vermont Agency of Transportation (VTrans, 2015) • Michigan DOT (MDOT, 2014) • South Dakota DOT (SDDOT, 2016) • North Carolina DOT (NCDOT, 2018)
Safety	• Geometric rating (roadway width or horizontal clearance) • Vertical clearances • Functional obsolescence • Inventory or operating rating • Crash density • Crash severity • Critical crash rate	• NCHRP Report 530 (Patidar et al., 2007) • Indiana DOT (Sinha et al., 2009) • North Carolina DOT (NCDOT, 2018)
Congestion Reduction	• Volume/capacity ratio • Existing volume (ADT) • Regional ADT impact	• Ohio DOT (ODOT, 2003) • Florida DOT (FDOT, 2012) • Georgia DOT (Amekudzi and Meyer, 2011) • New Jersey DOT (Szary and Roda, 2014) • North Carolina (NCDOT, 2018)
Vulnerability	• Scour vulnerability rating • Fatigue/fracture critical rating • Earthquake vulnerability rating • Other disaster vulnerability rating (Collision, Overload, Human-made) • Likelihood score • Consequence score	• NCHRP Report 590 (Patidar et al., 2007) • New York State DOT (NYSDOT, 2014) • CalTrans (Johnson, 2008) • Utah DOT (UDOT, 2014) • New Jersey DOT (Adams et al., 2014)
Economic Competitiveness	• User costs associated with detours • Impacts to local businesses • Area unemployment rate • Regional input and priority • Change in county economy • % change in long-term jobs	• Ohio DOT, (Ohio DOT 2003) • Vermont Agency of Transportation (VTrans, 2015) • North Carolina DOT (NCDOT, 2018, Chen and Johnston, 1987)
Multimodal, Freight,	• Load capacity	• NCHRP Report 590 (Patidar et al., 2007)

and Military Mobility	• Vertical clearance • Geometric clearance • Multimodal access and proximity • Accessibility • Truck volume • Truck % • Future interstate access	• Georgia DOT (Amekudzi and Meyer, 2011) Oregon DOT (Oregon DOT, 2015) • Oklahoma DOT (Oklahoma DOT, 2015) • CalTrans (Johnson, 2008; Johnson and Ozbek, 2013) • New York State DOT (NYSDOT 2014) • North Carolina DOT (NCDOT, 2018)
Functionality	• Functional deficiencies (often included under safety measures) • Functional performance measures (such as load capacity, often listed under freight measures) • Roadway alignment • Structure width	• NCHRP Report 590 (Patidar et al., 2007) • Indiana DOT (Sinha, 2009) • Oregon DOT (Oregon DOT, 2015) • Vermont Agency of Transportation (VTrans, 2013)
Maintenance	• Maintenance burden (frequency of actions, costs incurred) • Maintenance needs (cost, severity) • Environmental impacts	• South Dakota DOT (SDDOT, 2015) • Tennessee DOT (TDOT, 2017) • Colorado DOT (Harris and Laipply, 2013; CDOT, 2017) • South Carolina DOT (SCDOT, 2013)

Once agencies identify the appropriate performance goals and measures, the relative weights must be determined and specified. This can be done through the use of surveys and decision making techniques that help decision makers determine what criteria and measures are more or less important relative to each other. There are many methods for developing relative weights for each performance measure, including direct weighting, analytical hierarchy process (AHP), observed-derived weighting, and the gamble method (Patidar et al. 2007; Parlos, 2000). A description of each of these methods is provided in Appendix A, Section A.5.1.

3. Development of Guidelines for Prioritization of Bridge Replacement Projects

3.1 Overview of Research Methodology

The research effort was directed primarily through two approaches for developing a revised priority replacement index: practitioner-informed development of relative weights for performance measures through surveys and data-driven analysis of the significance of individual performance measures to the classification of bridges selected for replacement. The first approach was guided by the principles of NCHRP Report 590 and included two rounds of practitioner surveys. The objective of the first survey was to identify which performance measures identified within the literature review are deemed to be important by NCDOT engineers to the decision-making process for bridge replacement. In addition, the identification of any performance measures or factors not captured by the set of proposed performance measures or existing indices was also sought. Based on the results of the initial practitioner survey, a revised set of performance criteria and measures was developed, including previously unexplored performance measures quantifying the current maintenance needs identified in element-level inspections and the extent of maintenance burden that has been imposed by each structure in recent years to maintain an acceptable operational status. The development of these measures was informed through data-driven analysis of the North Carolina bridge inventory and was supported by a list of all active and scheduled bridge replacement projects. While this list could not reflect the relative priority of individual replacement projects against one another, it was assumed that bridges that have been identified for replacement have a greater priority for replacement than bridges not identified for replacement. The data-driven analysis and development of value functions for each performance measure required sourcing of data from previously unlinked databases, including the BMS, MMS, and additional GIS shapefiles maintained by NCDOT (Figure 3.1). The linking of these databases and development of scripts to extract and post-process the database records represents a major component of the effort expended over the course of this project. Whenever possible, automated scripts were developed as Excel macros to ensure consistent handling of data and to expedite the manipulation of the large sets of data.

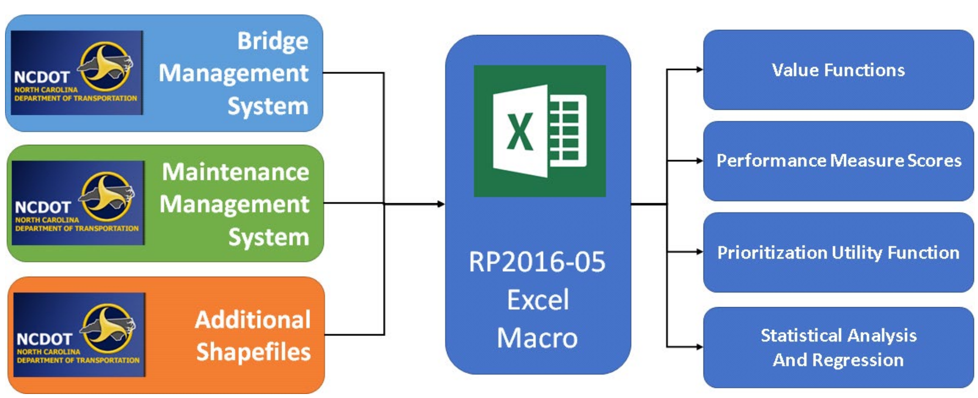


Figure 3.1. Schematic of data sourcing and analytics used to develop value functions and performance measures, compute prioritization formulas, and assess the performance of proposed models relative to the current replacement status for bridge in the BMS

Following sourcing and post-processing of data to develop the performance measures and associated value functions, a second practitioner survey was developed and distributed to Division Bridge Engineers, Bridge Maintenance Engineers, and members of the Steering and Implementation Committee. The objective of this second survey was to elicit practitioner preferences and risk attitudes to establish relative weights for the set of proposed performance criteria and measures. In parallel with the practitioner survey, the research team pursued statistical regressions to arrive at alternative prioritization formulae based on fitting the classification status of bridges in the state inventory. Binary logistic regression models were developed to provide a means of forecasting the probability that a bridge will be selected for replacement. Additionally, relative weights for each performance measures within an additive utility function were established through global optimization techniques with linear equality constraints. The prioritization formulae developed through the practitioner surveys and the statistical regressions were then assessed by comparing their ability to classify bridge replacement projects in the BMS as well as evaluating the distribution of scores generated by each formula. The current PRI scores were used as a basis for comparison to identify any improvements offered by the new formulae over the existing PRI approach.

3.2 Initial Practitioner Survey

On June 15, 2016, an initial practitioner survey was distributed to members of the Implementation and Steering Committee along with background material on the candidate performance criteria and measures developed through review of literature, legislation, and the state of practice for prioritization of transportation projects nationwide. This set of candidate performance criteria and measures included measures that have conventionally been used for prioritization of bridge replacement projects, such as condition ratings, functionality appraisals, and vulnerability appraisals, but also included additional measures to capture the potential impacts on safety, congestion reduction, freight mobility, and multimodal transportation (Figure 3.2). Similar measures have been incorporated into the prioritization methodologies utilized by NCDOT under State Transportation Improvement Program (STIP). Although bridge replacement projects are exempt from the prioritization requirements outlined within the State Transportation Investments (STI) legislation, the research team needed to assess through a practitioner survey whether any of these measures are significant considerations when selecting bridge replacement project so that a new priority replacement index would sufficiently capture factors that may not have been previously included within past bridge replacement prioritization tools. The initial practitioner survey followed guidance from NCHRP Report 590 and included Direct Weighting, Analytic Hierarchy Process, and Mid-Value Splitting Technique surveying instruments. The complete survey is presented in Appendix B along with the responses received.

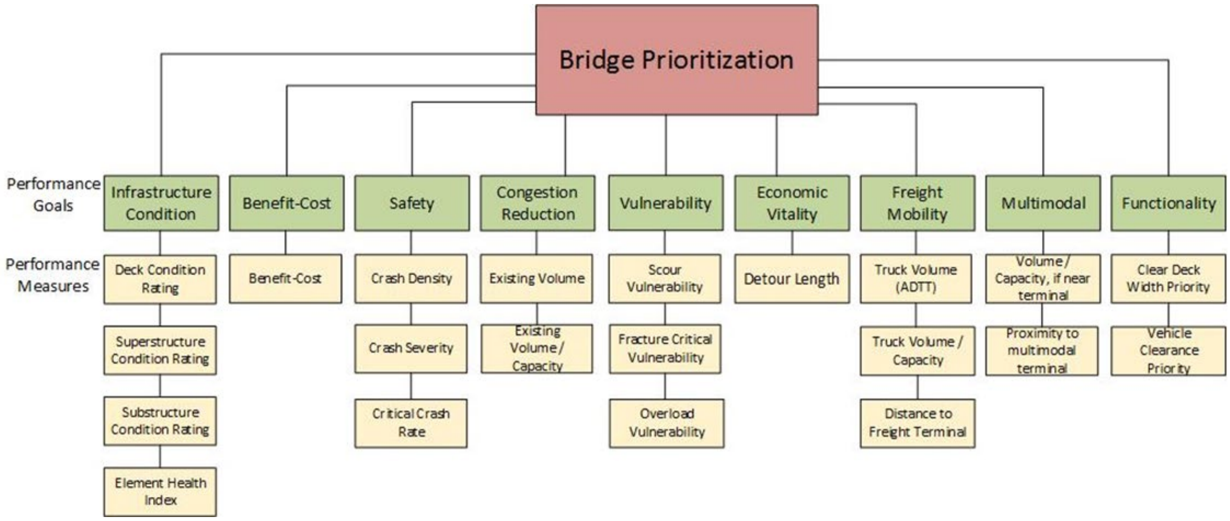


Figure 3.2. Initial set of proposed performance criteria and measures for new priority replacement index

The initial practitioner survey was circulated to only a limited participant group and was terminated after only three responses were received due to respondent confusion related to the mid-value splitting technique questions and a general consensus that many of the performance criteria and measures assessed within this survey were not significant for prioritization of bridge replacement projects. The limited responses that were received were combined with feedback from members of the Steering and Implementation Committee to ultimately revise the set of proposed performance criteria and measures. With respect to the survey responses, the average relative weights developed from the Direct Weighting portion of the initial practitioner survey are presented in Table 3.1. These results indicated that only the infrastructure condition, vulnerability, and functionality performance criteria are significant to prioritization of bridge replacement projects, although some select performance measures within other proposed criteria, such as detour length and truck volume should also be retained in the prioritization formula. Feedback from members of the Steering and Implementation Committee was that many of the performance criteria and measures used by the NCDOT for other transportation projects do not influence bridge replacement decisions. Furthermore, the research team was encouraged to use data-driven analysis to propose new performance criteria and performance measures to quantify factors affecting the prioritization of bridge replacement projects that are not already captured by ratings or appraisals incorporated in the PRI. Specifically, the research team was encouraged to investigate ways to incorporate the current extent of maintenance need identified through the bridge inspection program as a means of providing more granularity than offered by the general condition ratings on the scale of the required maintenance needed to restore a structure to desirable condition ratings. The research team was also encouraged to associate the maintenance need with priority of the maintenance actions by leveraging element-level inspection data incorporated in the BMS. It was communicated to the research team that bridges prioritized for replacement are often “problem” structures, where a division has needed to routinely respond to maintenance needs year after year and in some case perform the same maintenance actions on the same structure to maintain the level of service. The research team was tasked with producing a maintenance burden performance criteria and associated performance measures that could be used to quantify the extent of burdensome maintenance performed on individual structures, including reoccurring maintenance, in order to associate this historical maintenance burden with an increased priority for bridge replacement. The following section of this report details the revision of the proposed performance criteria and measures for the new priority replacement index, including the development of these maintenance needs and maintenance burden performance criteria.

Table 3.1: Summary of Relative Weights for Performance Criteria and Measures Derived from Initial Practitioner Survey

Criterion or Measure	Weight
Infrastructure Condition	**44.0**
Deck Condition Rating	9.7
Superstructure Condition Rating	15.3
Substructure Condition Rating	17.3
Element Health Index	1.7
Vulnerability	**17.7**
Scour Vulnerability	4.0
Fracture Critical Vulnerability	7.3
Overload Vulnerability	6.3
Functionality	**11.7**
Clear Deck Width Priority	7.7
Vehicle Clearance Priority	4.0
Freight Mobility	**7.7**
Truck Volume (ADTT)	4.7
Truck Volume / Capacity	2.3
Distance to Freight Terminal	0.7
Economic Vitality	**5.7**
Detour Length	5.7
Congestion Reduction	**4.7**
Existing Volume	2.7
Existing Volume / Capacity	2.0
Benefit-Cost	**4.0**
Benefit-Cost	4.0
Safety	**3.3**
Crash Density	1.3
Crash Severity	1.3
Critical Crash Rate	0.7
Multimodal	**1.3**
Volume / Capacity	0.7
Proximity to multimodal terminal	0.7

Rank	Performance Measure	Weight
1	Substructure Condition Rating	17.3
2	Superstructure Condition Rating	15.3
3	Deck Condition Rating	9.7
4	Clear Deck Width Priority	7.7
5	Fracture Critical Vulnerability	7.3
6	Overload Vulnerability	6.3
7	Detour Length	5.7
8	Truck Volume (ADTT)	4.7
9	Scour Vulnerability	4.0
10	Vehicle Clearance Priority	4.0
11	Benefit-Cost	4.0
12	Existing Volume	2.7
13	Truck Volume / Capacity	2.3
14	Existing Volume / Capacity	2.0
15	Element Health Index	1.7
16	Crash Density	1.3
17	Crash Severity	1.3
18	Critical Crash Rate	0.7
19	Distance to Freight Terminal	0.7
20	Volume / Capacity	0.7
21	Proximity to multimodal terminal	0.7

3.3 Revised Set of Performance Criteria and Measures

Following the feedback received from the initial practitioner survey, the proposed set of performance criteria and associated measures were revised to exclude metrics that were found to be insignificant to the prioritization of bridge replacement projects. Additionally, the performance criteria were expanded to include additional factors not captured within the initial set. Specifically:

1) The benefit-cost, safety, congestion reduction, and multimodal performance criteria were eliminated since the relative weighting each of these performance criteria received in the initial practitioner survey was less than 5%.
2) The freight mobility performance criterion was generalized to a generalized mobility performance criterion. The mobility criterion is intended to reflect the usage of the bridge as well as the potential impact of closure on the community. The distance to freight terminal performance measure in this criterion was eliminated, since it received low importance within the initial survey and computing this measure would not be possible without introducing databases not currently available in the AMS. The truck volume/capacity performance measure was also eliminated as collinearity was expressed between the truck volume and truck volume/capacity performance measures when applied to the data in the BMS. Average daily traffic (ADT), bridge posting rating, system classification and detour length were added as additional performance measures to the new mobility performance criterion.
3) The economic vitality performance criterion was eliminated, with the detour length performance measure being reassigned to the mobility performance criterion. This change was made at the suggestion of members of the Steering and Implementation Committee, who felt that economic vitality was an unconventional terminology to associate with detour length.
4) Within the infrastructure condition performance criterion, the element health index was eliminated. The elimination of this measure was driven partially by the low relative weighting this measure received in the initial survey and partially by the introduction of maintenance needs performance criteria that would leverage element level ratings.
5) Within the vulnerability performance criterion, the overload vulnerability performance measure was eliminated following the introduction of the bridge posting rating in the mobility performance criterion.
6) Within the functionality performance criterion, the clear deck width priority and vehicle clearance priority were replaced with the deck geometry rating, vertical underclearance rating, and horizontal underclearance rating. This change was made because these NBI ratings are directly available in the BMS and avoid the nonlinearities present in the clear deck width priority and vehicle clearance priority measures that can obscure the relative influence of the individual performance measures.
7) Lastly, to address specific shortcomings of the PRI previously discussed, performance criteria seeking to quantify current maintenance needs as well as recent maintenance burden were developed. The goal of these performance criteria was to leverage valuable data from the AMS to quantify the extent of maintenance or rehabilitation work necessary

to restore each structure to desired condition ratings and to quantify the extent of maintenance investments that have been made for each structure within the last decade.

3.3.1 Maintenance Needs Criterion and Measures

The objective of the first of the newly introduced criteria, maintenance needs, is to provide a means of reflecting the extent of work that would need to be performed in order to rehabilitate the structure to desirable condition ratings as well as the urgency with which this work would need to be performed. The rationale behind this performance criterion is that structures with extensive and costly maintenance needs would likely be more suitable candidates for replacement than structures that could be rehabilitated to improve condition and extend service life through less costly interventions. Likewise, the urgency of the required maintenance action should be reflected in the priority for replacement.

To produce performance measures for the maintenance needs criterion, element level ratings from the most recent set of bridge inspection records are indirectly used to quantify the extent of maintenance needs for each individual structure. During bridge inspections, maintenance actions necessary to restore the condition of bridge elements to desirable levels are identified by the bridge inspector. Currently, these element level inspection results are aggregated into counts of the total quantity of individual maintenance actions recommended for each structure and stored in an Inspector Recommended Maintenance Needs database in the BMS. Based on the severity of the element condition, these inspector recommended maintenance actions are classified as either critical, priority, or recommended. Critical maintenance needs are required to be addressed immediately, so they are not observed within the Inspector Recommended Maintenance Needs database in the BMS. Priority needs reflect the next level of urgency for maintenance action, while recommended needs are actions that have even less urgency but are still necessary to restore bridge element condition ratings to desirable levels.

Two performance measures were developed to serve as metrics for the maintenance needs performance criterion: total cost of priority maintenance needs and total cost of recommended maintenance needs. These performance measures are readily computed using existing databases in the BMS, as the Inspector Recommended Maintenance Needs database provides aggregated quantities of individual maintenance actions specified during the most recent inspection cycle for the structure. The BMS also utilizes estimated unit costs to perform project and network-level forecasting and these estimated unit costs can be used with the aggregated quantities of priority and recommended maintenance needs to determine the total estimated cost of each classification of maintenance need.

3.3.2 Maintenance Burden Criterion and Measures

In addition to reflecting the extent of required maintenance in the priority replacement index, a performance criterion reflecting recently completed maintenance actions on each structure was developed. This maintenance burden performance criterion reflects the amount of resources that have already been invested recently in the structure to maintain a desired operational condition and also attempts to isolate "problem" bridges requiring repeated maintenance year after year. Development of performance measures for the maintenance burden criterion leveraged the historical maintenance records stored within the Maintenance Management System (MMS) of the AMS. These records use a list of over 200 standard maintenance actions and indicate the time and type of the applied action as well as the cost. The maintenance records used for the development of the performance measures within the maintenance burden criterion include the most recent ten years of maintenance performed on the structure.

The developed performance measures for the maintenance burden criterion assess the cost and frequency of completed maintenance actions on each bridge to determine if previous expenditures indicate that bridge replacement would alleviate burdensome and potentially costly maintenance actions that have been ineffective or only partially effective in prolonging the service life of the structure. The two performance measures are the total cost of maintenance actions performed on the bridge and the total cost of reoccurring maintenance actions performed on the bridge. Reoccurring maintenance actions are instances when the same type of maintenance was performed at separate times over the ten year period. Instances of reoccurring maintenance are assumed to reflect a greater burden to highway divisions than single instance maintenance actions because they suggest a repeated allocation of resources to maintain acceptable level of service on a potentially problematic structure. In recognizing that not all maintenance actions are burdensome, the performance measures were further divided into classifications of action: burdensome repairs and maintenance, major rehabilitation investments, and preservation treatments. Each of the maintenance actions were classified into these categories in order to distinguish actions that could increase the likelihood of bridge replacement (burdensome repairs and maintenance) or reduce the likelihood of bridge replacement due to prolonged service life afforded by the actions (major rehabilitation investments and preservation actions). The assumption made is that bridges that have received major rehabilitation or preservation treatments are less likely to be priority candidates for replacement since NCDOT has likely not yet received the service life benefits of these investments. In contrast, bridges that have required significant maintenance for repairs that do not significantly improve the overall condition of the bridge are more suitable for replacement, particularly if the maintenance has been performed on multiple occasions. In addition to these classifications, there are some maintenance actions that have no effect of the decision to replace a bridge (actions such as removal of graffiti, sign replacement, and maintenance of erosion control devices). Such actions were identified in a separate category and removed from all subsequent analysis.

The classification of each maintenance action was determined through engineering judgement, but subsequently reviewed and approved by the members of the Steering and Implementation Committee at an interim project meeting in May 2017. Table 3.2 provides examples of maintenance actions within each classification. Major rehabilitation investments included replacement of key bridge components, such as bents, piers, superstructures, and joints. On average, these major rehabilitation investment actions were found to occur the least frequently over the ten years analyzed, but are generally the most expensive individual maintenance actions and account for approximately 17% of the total maintenance dollars recorded in the MMS. Preservation actions were defined to include cleaning and washing of structural components, painting of structural steel, maintaining drainage systems, and deck sealing and overlays. While there are a significant number of preservation actions recorded in the MMS database, the costs associated with these actions is generally small compared to the cost of other maintenance actions and the total amount spent on preservation actions was found to represent only 5% of all actions recorded in the MMS. Burdensome maintenance and repairs was defined to include all maintenance actions associated with the maintenance and repair of any superstructure, substructure, or deck components, deck and asphalt patching, and other maintenance and repair actions that were deemed to be significant to maintaining the structural condition and functionality of the structure. The costs of burdensome actions are generally less than the costs of major rehabilitation investments, yet greater than the costs of preservation actions. The majority of the MMS historical database was found to consist of burdensome maintenance and repair actions, with such actions accounting for approximately 53% of the total costs indexed in the database. Lastly, actions insignificant to bridge replacement included surveying, vegetation management, brush and tree control, beaver control, graffiti removal, maintenance to hand rails and signs, and other such actions. It should be noted that, while the costs of these individual actions were usually low relative to other maintenance actions, they were found to account for about 25% of the total costs recorded in the MMS database.

Table 3.2. Maintenance action classifications and examples

Classification	**Maintenance Action Examples**
Burdensome Repairs and Maintenance	Maintenance and repair of any superstructure, substructure, or deck component; deck and asphalt patching; other actions related to repair and maintenance
Major Rehabilitation Investments	Replacement of key bridge component, such as bents, piers, substructures, and joints
Preservation	Cleaning and washing of components; painting of structural steel; maintaining drainage systems; deck sealing and overlays
Insignificant to replacement priority	Surveying; brush and tree control; beaver control

Within this research effort, the maintenance burden performance measures were calculated using ten years of historical maintenance records sourced from the MMS. An Excel macro was created to process the historical records by pre-filtering the maintenance actions into the developed classifications and sum the total cost of all maintenance actions performed on each structure over the prior ten years for each maintenance action classification. In this way, the total cost of burdensome repairs and maintenance, total cost of major rehabilitation investments, and total cost of preservation actions applied to each structure over the past ten years was computed and linked to the bridge records sourced from the BMS Network Master. In addition, a PivotTable was used in Excel to identify instances where the same maintenance action was performed on the same structure more than one year of the time frame analyzed. This was done by organizing the rows of the MMS database by structure ID and then by the total cost for each individual maintenance action by the year performed. If a maintenance action repeated on multiple years, then it was considered to be a reoccurring maintenance action. As previously noted, reoccurring maintenance actions are expected to be more strongly correlated with preference to replace bridges due to the resources and costs associated with routinely performing the same actions on the same structure to maintain the level of service. To account for the classifications of maintenance actions, the total costs of reoccurring burdensome repairs and maintenance, total cost of reoccurring major rehabilitation investments, and total cost of reoccurring preservation actions applied to each structure over the past ten years were computed and linked to the bridge records in the BMS Network Master.

Statistical analysis of the proposed maintenance burden performance measures was performed in order to assess their significance to prioritization of bridge replacement projects. The Network Master does not indicate the status or ranking of bridges currently selected for replacement and NCDOT does not maintain a singular list that contains all of the bridges selected for replacement with their prioritized rank. However, a list of active bridge projects was provided to the research team and the baseline plan (BMIP) from the BMS was used to identify bridges that have been identified for future replacement. It was assumed that all current and scheduled bridge replacement projects were contained within these two lists and that bridges scheduled for replacement carry a higher priority for replacement than bridges that are not scheduled for replacement. It is important to note that the absolute priority of individual bridge replacement projects relative to each other is not assessed or recorded by NCDOT so all statistical analysis and regression performed within this report was limited to binary classification (either scheduled for replacement or not scheduled for replacement).

The BMIP list contains the structure identification number, so all bridges scheduled for future replacement could be identified with little effort. The list of active bridge projects did not include the structure identification numbers or sufficiently detailed descriptions of the scope of work, so additional preprocessing and verification of this list of bridge projects was necessary. This list contained three useful identifiers for linking the projects on the list to bridges in the BMS: the project contract number, the Transportation Improvement Program (TIP) number, and the WBS element number. The list of active bridge projects contained all bridge projects, including rehabilitation and repair contracts, so the first step in the preprocessing of this list was to isolate only the projects involving a bridge replacement. First, keywords that would indicate bridge replacement were queried in the contract description and location columns of each record to filter only the bridge projects associated with replacements. Specifically, the contract description needed to contain either "Structure", "Str", "bridge", or "replacement" and could not contain either "preservation" or "rehabilitation." For all records meeting the keyword filtering criteria, the associated project contract documents were then manually search for on the NCDOT Connect bidding and letting document database. The associated project contract documents were then manually reviewed to both confirm that the project was a replacement project and to identify the corresponding structure number. This manual review of contract documents was also effective in identifying instances where more than one bridge was replaced under the same contract.

Additional data verification checks performed on both the list of active bridge projects and BMIP list included: duplicate record checks, bridge age and status confirmations, and review of infrastructure condition ratings. An assumption was made that if none of the infrastructure condition ratings were lower than 7, then the data listed in the Network Master contained performance measure data for the newly replaced bridge and not a bridge actively being replaced.

In total, 258 active bridge replacement projects were identified from the list of active bridge projects and successfully linked to specific structure numbers in the Network Master. An additional 991 bridge replacement projects were identified and manually verified from the BMIP database, resulting in a total of 1,249 bridges identified as bridges selected for replacement. This represents just over 9% of the 13,834 total number of bridges in the state bridge inventory at the time that the Network Master was sourced for this analysis.

The potential predictive value of each of the possible performance measures developed for the maintenance burden criterion was evaluated by assessing any differences in historical maintenance costs for bridges in the state inventory that are current scheduled for replacement and bridges that are not currently scheduled for replacement. An Excel macro was developed in order to compile the historical costs spent on burdensome maintenance and repairs, major rehabilitation investments, and preservation actions for each individual bridge within the current Network Master. Results for the total dollars spent on each category are presented in Figure 3.3. This figure presents empirical cumulative distribution functions, which are essentially cumulative histograms. These plots can be interpreted as follows: at any point along the function, the cumulative fraction of bridges is the percentage of the state bridge inventory that received the same total dollars spent or less. For example, Figure 3.3a indicates that approximately 40% of the bridges scheduled for replacement have no record of burdensome repairs and maintenance costs in the MMS, while approximately 65% have received $10,000 or less in burdensome repairs and maintenance, and just over 90% have received $50,000 or less (or conversely, just under 10% have received more than $50,000) in burdensome repairs and maintenance.

The comparison between bridges scheduled for replacement and not scheduled for replacement indicates that there is a significant difference in burdensome maintenance and repair costs for bridges scheduled for replacement relative to the other bridges in the inventory, with a larger percentage of bridges scheduled for replacement having incurred historical burdensome maintenance and repair and costs and significantly larger total burdensome maintenance and repair costs on average (Figure 3.3a). However, when dollars invested in major rehabilitation investment actions and preservation actions were analyzed, there were found to be no statistically significant differences between the historical costs incurred on structures currently scheduled for replacement compared to all other structures in the current inventory (Figures 3.3b and 3.3c). This suggests that additional performance measures associated with recent investments in major rehabilitation actions or preservation actions should not be introduced to the maintenance burden performance criteria for the new prioritization index. These measures may however be valuable for other potential prioritization indices for identifying and ranking preservation or rehabilitation projects. While the results suggest that additional performance measures for preservation actions and major rehabilitation actions should not be introduced, the analysis does indicate that the performance measure for maintenance burden costs will be improved if these costs are removed from the measure rather than included. Figure 3.3d presents the value functions for total dollars spent on maintenance actions where all significant maintenance actions are included (burdensome maintenance and repairs, major rehabilitation investments, and preservation actions). While there is a significant difference in the value functions for bridges scheduled for replacement and those not scheduled for replacement, the difference is not as significant as when only burdensome maintenance and repairs are considered (Figure 3.3a). Therefore, the recommended performance measure for total dollars spent on maintenance actions only includes the maintenance actions associated with burdensome maintenance and repairs and not any actions that are classified as preservation actions or major rehabilitation investments.

The results obtained from a similar analysis conducted with reoccurring maintenance actions is presented in Figure 3.4. While reoccurring maintenance actions occur less frequently, the results are similar to those obtained for total costs spent on maintenance actions. A significant difference in reoccurring costs for burdensome maintenance and repairs is observed for bridges scheduled for replacement relative to bridges that are not scheduled for replacement. There are no statistically significant differences in reoccurring costs spent on major rehabilitation investments and preservation actions. It should be further noted that reoccurring major rehabilitation investments and preservation actions were found to be extremely rare, while reoccurring burdensome maintenance was found to occur more frequently. Again, by removing major rehabilitation actions and preservation actions from the total reoccurring maintenance costs, an improved distinction between bridges scheduled for replacement relative to all other bridges is developed. Therefore, this additional analysis indicates that both performance measures (total dollars spent on prior maintenance actions and total dollars spent on reoccurring prior maintenance actions) should be computed using only maintenance actions designated as burdensome maintenance and repairs to improve the ability of the performance measures to distinguish bridges that have a higher priority for replacement.

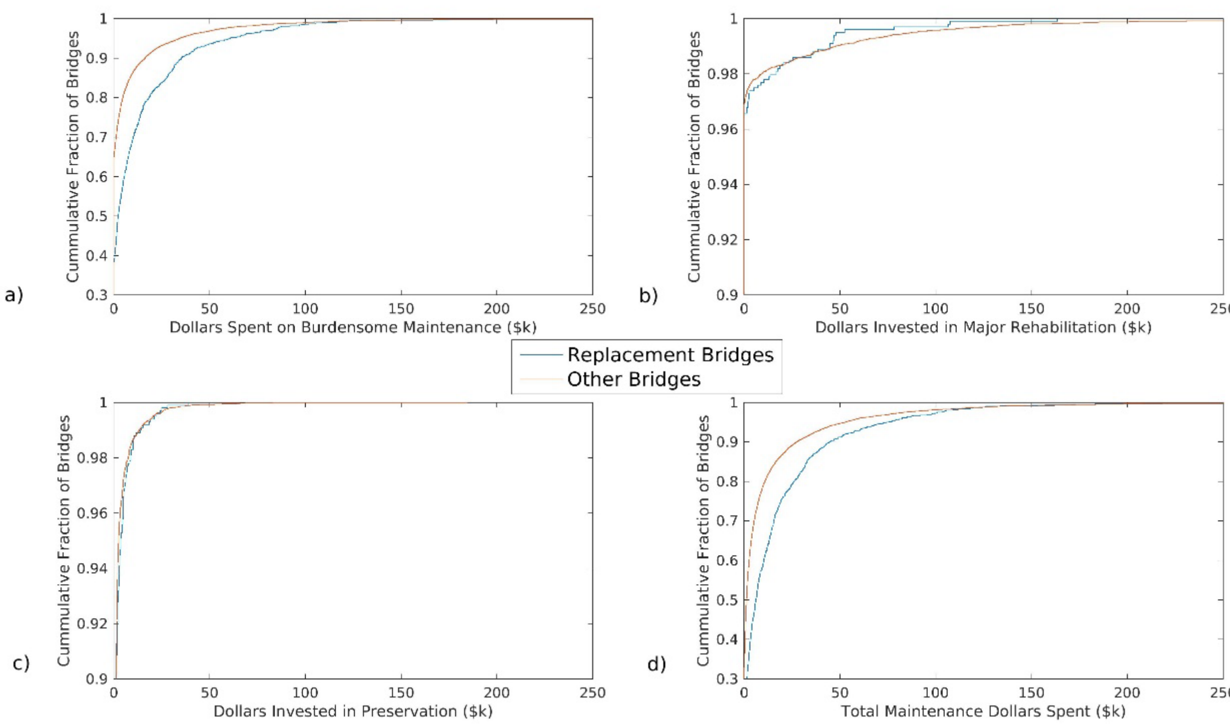


Figure 3.3. Empirical Cumulative Distribution Functions for Total Maintenance Costs for Bridges Currently Scheduled for Replacement and All Other Structures

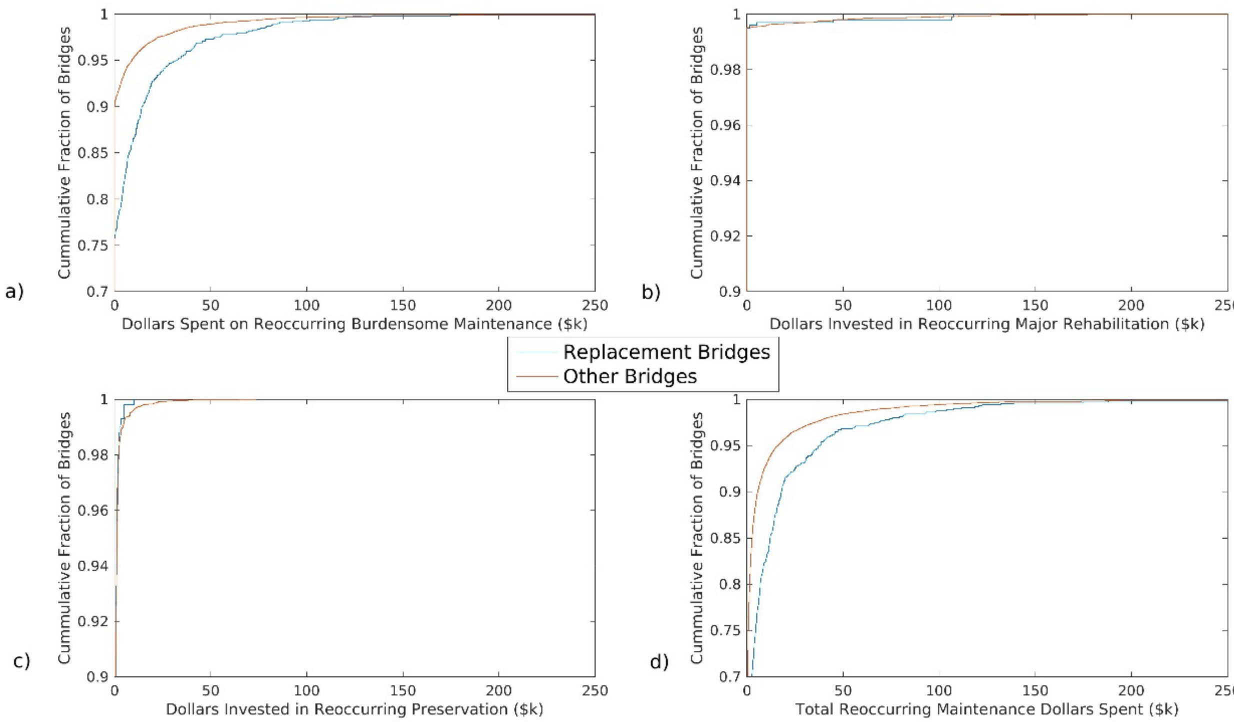


Figure 3.4. Empirical Cumulative Distribution Functions for Reoccurring Maintenance Costs for Bridges Currently Scheduled for Replacement and All Other Structures

3.3.3 Summary of Proposed Performance Criteria and Measures

Following revision of the initially proposed set of performance criteria and measures and the development of new performance measures to introduce the maintenance needs and maintenance burden criteria, a new tree structure for the proposed performance metrics of a new priority replacement index was finalized (Figure 3.5). These proposed performance criteria and measures were approved by members of the Steering and Implementation Committee during a May 2017 interim project meeting. The first four performance criteria utilize established performance measures that have been previously incorporated into prior indices, such as the PRI and Sufficiency Rating. The last two performance criteria and their associated measures are new innovations that are expected to enhance the ability of the new priority replacement index to identify and rank bridges likely to be selected for replacement using a previously undeveloped link between the BMS, element level inspection data, and MMS.

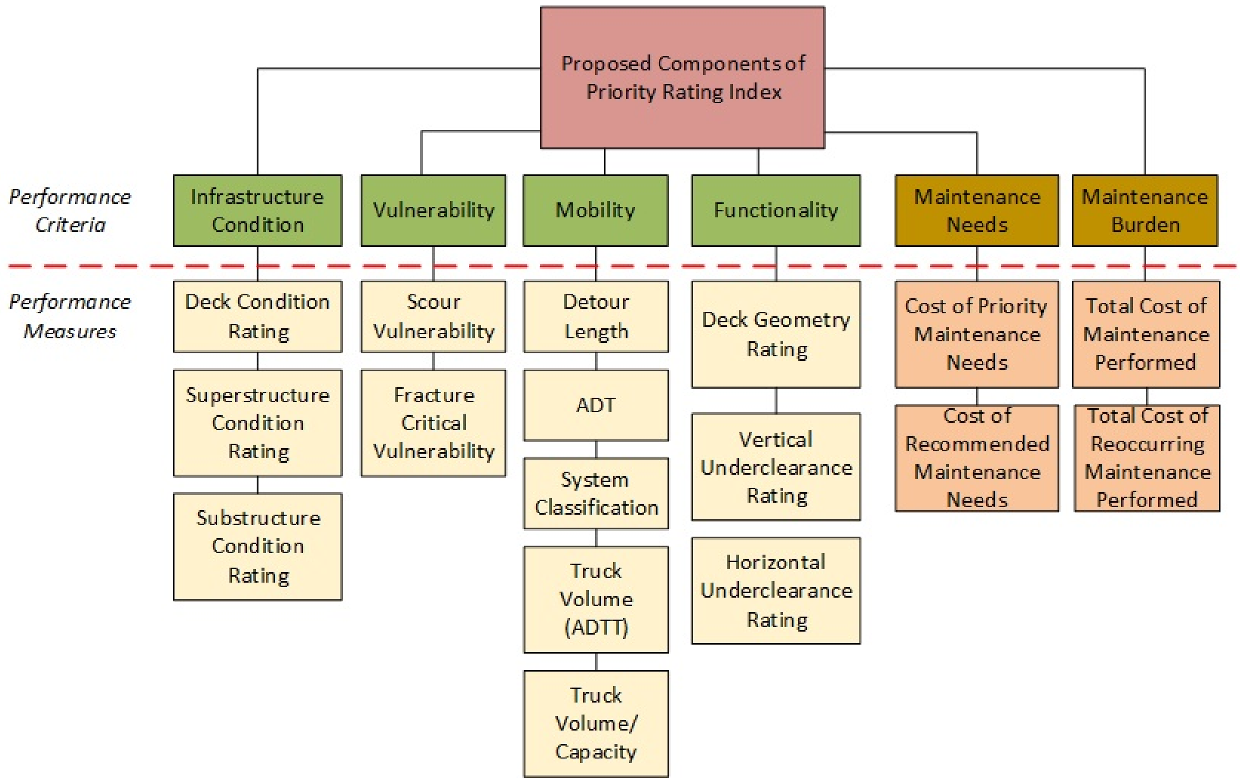


Figure 3.5. Revised set of proposed performance criteria and measures for the new priority rating index

3.4 Final Practitioner Survey

On February 21, 2018, a final practitioner survey was distributed to Division Bridge Program Managers, Bridge Maintenance Engineers, and members of the Steering and Implementation Committee. The complete survey is presented in Appendix C along with a summary of the responses received. This survey was also prepared using the general guidance from NCHRP Report 590, however the mid-value splitting technique was not used due to the difficulty encountered with this surveying technique during the initial practitioner survey. Also, for ease of implementation, the survey was created on the SurveyShare platform and distributed to the list of participants through a hyperlink. The survey was initially structured with a response window that would close on March 16, 2018, but due to a slow rate of completion, the window was extended. On May 24, 2018, the last of the participant responses was received. In total, 23 complete or nearly complete survey responses were received. The respondents consisted of 14 Division Bridge Program Engineers, 6 Bridge Maintenance Engineers, and 3 engineers from the SMU. All of the 14 highway divisions were represented by at least one survey respondent, with the exception of Division 5.

Within the Direct Weighting portion of the survey, respondents were asked to allocate a fixed number of points to each performance criteria and subsequently to each performance measure within the individual performance criteria to specify their relative importance to the priority for bridge replacement. Table 3.3 presents a summary of the processed results from the Direct Weighting portion of the final practitioner survey, where averaged responses from Division Bridge

Program Managers, Bridge Maintenance Engineers, and members of the SMU presented individually alongside the average response recorded across all respondents. The results exhibit generally strong consensus about the relative importance of the individual performance criteria as well as performance measures across the survey respondents. In particular, there was exceptionally strong consistency between the average responses received by Division Bridge Program Managers and Bridge Maintenance Engineers with no particularly notable differences in their assigned weights. Engineers from the SMU did allocate slightly larger significance to the infrastructure condition and maintenance needs performance criteria with notably less weight applied to the vulnerability performance criterion. In aggregate, survey respondents indicated that the infrastructure condition is the most important performance criterion, receiving nearly double the weighting of any of the other performance criteria. The vulnerability, mobility, maintenance burden, and maintenance needs performance criteria were ranked sequentially in this order of importance, with nearly equal weight being assigned to each criterion. The functionality performance criterion received the lowest relative weighting, although the relative magnitude of the weighting for this measure does indicate that it is significant to the prioritization of bridge replacement projects. Table 3.4 presents the same processed results from the Direct Weighting portion of the practitioner survey with the individual performance measures ranked by their identified relative significance. According to direct weighting, the respondents place greatest significance on substructure and superstructure condition ratings, followed by fracture critical rating, and the extent of priority maintenance needs. Mobility and functionality performance measures were consistently ranked as having the least significance on the prioritization of bridge replacement projects.

In addition to Direct Weighting, a portion of the survey utilized the Analytic Hierarchy Process as a tool for eliciting the relative weighting of the proposed performance criteria and measures. In contrast to the Direct Weighting approach that allows respondents to directly indicate the relative weights across all criteria or measures, the Analytic Hierarchy Process requires respondents to individually assess the relative importance of performance criteria or measures through pairwise comparisons. In each comparison, the respondent is asked to identify which of the two options is more significant and the extent of the significance (equal, slightly, moderately, strongly, or extremely). The pairwise comparisons are assembled into a matrix, from which the relative weights can be deduced from the unit normalized eigenvector associated with the largest eigenvalue of the matrix. Since the comparisons are performed pairwise, the Analytic Hierarchy Process simplifies the complexity of assessing trade-offs between a large set of different performance criteria and measures concurrently, as required by the Direct Weighting surveying method. However, since the Analytical Hierarchy Process decomposes the ranking process into a large number of sub-problems, there is also a greater potential for inconsistencies to arise in the aggregation of responses from an individual survey respondent. For instance, if a respondent indicates that criterion A is more significant than criterion B and criterion B is more significant than criterion C, then there will be an inconsistency if during a subsequent pairwise comparison the same respondent indicates that criterion C is more important than criterion A. To identify the presence of significant inconsistencies in a respondents pairwise comparisons, a Consistency Index (CI) is calculated and compared to a Random Index, which is a measure of what the expected CI would be if the responses were completely randomized. The ratio of the CI to the RI is a measure referred to as the Consistency Ratio (CR), which is used as a threshold to admit survey responses with reasonable enough consistency. The recommended threshold for the CR is 0.10 or a maximum relative inconsistency of 10% (Saaty, 1987). This threshold permits some degree of inconsistency amongst the pairwise comparisons provided by each respondent but ensures that there is enough consistency to reflect the practitioner's true preference structure. Additional information on the Analytic Hierarchy Process approach is provided in Appendix A, Section A.5.1.2.

Table 3.3: Summary of Relative Weights for Performance Criteria and Measures Derived from Direct Weighting Portion of Practitioner Survey

	Division	**Maint.**	**SMU**	**All**
Infrastructure Condition	**28.6**	**28.3**	**33.4**	**29.1**
Deck	7.0	7.5	9.6	7.4
Superstructure	10.2	10.3	11.9	10.5
Substructure	11.4	10.5	11.9	11.2
Vulnerability	**17.7**	**16.6**	**8.3**	**16.1**
Scour	7.3	6.8	4.4	6.8
Fracture Critical	10.4	9.8	3.9	9.3
Mobility	**15.4**	**15.9**	**16.6**	**15.4**
Detour Length	2.4	2.4	2.5	2.4
ADT	3.0	2.9	2.9	2.9
Primary	0.8	1.3	1.0	0.9
Secondary	0.5	0.9	0.6	0.6
Interstate	1.0	1.8	1.4	1.2
Bridge Posting	5.4	4.1	5.4	5.1
Truck Volume (ADTT)	2.3	2.4	2.9	2.3
Functionality	**10.2**	**11.7**	**11.7**	**11.0**
Deck Geometry Rating	2.9	2.9	4.7	3.2
Vertical Underclearance	4.5	5.0	4.5	4.7
Horiz. Underclearance	2.8	3.8	2.5	3.1
Maintenance Needs	**13.7**	**14.2**	**16.7**	**14.1**
Priority Needs	8.7	8.5	11.7	9.0
Recommended Needs	5.0	5.7	5.0	5.1
Maintenance Burden	**15.1**	**13.4**	**13.3**	**14.2**
Burdensome	7.2	5.9	7.3	6.8
Reoccurring	7.9	7.5	6.0	7.4

Table 3.4: Ranking of Significance of Individual Performance Measures Derived from Direct Weighting Portion of Practitioner Survey

Rank	Performance Measure	Division	Maint.	Central	All
1	Substructure	11.4	10.5	11.9	11.2
2	Superstructure	10.2	10.3	11.9	10.5
3	Fracture Critical	10.4	9.8	3.9	9.3
4	Priority Needs	8.7	8.5	11.7	9.0
5	Deck	7.0	7.5	9.6	7.4
6	Reoccurring	7.9	7.5	6.0	7.4
7	Burdensome	7.2	5.9	7.3	6.8
8	Scour	7.3	6.8	4.4	6.8
9	Recommended Needs	5.0	5.7	5.0	5.1
10	Bridge Posting	5.4	4.1	5.4	5.1
11	Vertical Underclearance	4.5	5	4.5	4.7
12	Deck Geometry Rating	2.9	2.9	4.7	3.2
13	Horiz. Underclearance	2.8	3.8	2.5	3.1
14	ADT	3.0	2.9	2.9	2.9
15	Detour Length	2.4	2.4	2.5	2.4
16	Truck Volume (ADTT)	2.3	2.4	2.9	2.3
17	Interstate	1.0	1.8	1.4	1.2
18	Primary	0.8	1.3	1.0	0.9
19	Secondary	0.5	0.9	0.6	0.6

Of the 23 survey responses received, typically only 10 responses to the Analytic Hierarchy Process questions were deemed sufficiently consistent when four or more performance criteria or measures were assessed within the comparisons. For survey questions assessing three or fewer performance criteria or measures using the Analytic Hierarchy Process, the number of consistent responses typically ranged from 10 to 20. It should be noted that a few respondents chose not to respond to the Analytic Hierarchy Process questions and some respondents omitted a response to one or more questions. The relative weights were computed for all of the survey responses that were completed for each individual comparison and only those responses that were deemed to be sufficiently consistent according to the CR were included within an aggregated assessment of the preference structure for the complete group of respondents. Due to the limited number of consistent responses received within the Analytic Hierarchy Process portion of the survey, the responses were not analyzed independently for Division Bridge Program Managers, Bridge Maintenance Engineers, and members of the Structures Management Unit.

Table 3.5 provides the relative weights for each of the performance criteria and measures as determined by the Analytic Hierarchy Process, as well as the weights for the individual performance measures ranked by the identified significance. Across all consistent responses received there was greater variability in the computed relative weights than observed within the Direct Weighting portion of the survey. However, despite this greater variability amongst the survey responses, the weighting of individual performance measures within each performance criteria was generally consistent with that identified through the Direct Weighting process. This consistency in the weighting of performance measures within performance criteria strongly implies that the preference structure of the practitioners was captured by the surveying tool. The most significant difference between the Direct Weighting results and the Analytic Hierarchy Process results was that the Analytical Hierarchy Process found a significantly greater importance for the maintenance burden and maintenance needs performance criteria with correspondingly less importance for the vulnerability and mobility performance criteria. As a result of the greater weighting toward maintenance burden and maintenance needs performance criteria, the reoccurring burdensome maintenance cost and priority maintenance needs performance measures were identified as the two most significant performance measures for prioritization of bridge replacement projects, followed by the substructure condition rating, non-reoccurring burdensome maintenance cost, and superstructure condition rating.

The reason for the significant difference in relative weighting assigned to the maintenance needs and maintenance burden performance measures within the Analytic Hierarchy Process and Direct Weighting is likely a result of the lack of prior established used of the performance measures within these two criteria. The existing PRI and other prioritization methodologies used by NCDOT do not currently use measures that compute the current maintenance needs and historical maintenance burden, so respondents may have under-estimated their significance to the preference structure when directly providing weights to these criteria. Since it is clear from survey comments that Division Bridge Program Managers and Bridge Maintenance Engineers often consider the extent of maintenance need and also give priority to "problem" bridges that have required repeated maintenance, the survey respondents were likely familiar with the objective of each of the performance criteria. When assessing the significant of these performance criteria in the less complex pairwise comparisons performed within the Analytical Hierarchy Process portion of the survey, the true significance of these maintenance-related performance measures and criteria may have been elicited more accurately by this alternative surveying technique.

Since the Direct Weighting and Analytic Hierarchy Process surveys produced different relative weights for the performance criteria, the recommendation for the use of either set of relative weights for the new priority replacement index will be guided by statistical analysis of indices derived from each method applied to data from the BMS. The following subsections detail the sourcing of data and development of value functions for this statistical analysis as well as the methodology used to compare the performance of developed indices in forecasting the classification of current and future bridge replacement projects.

Table 3.5. Summary of Relative Weights for Performance Criteria and Measures Derived from Analytical Hierarchy Process Portion of Practitioner Survey

Criteria or Measure	Weight
Infrastructure Condition	**26.0**
Deck	5.6
Superstructure	9.5
Substructure	10.9
Vulnerability	**9.3**
Scour	3.0
Fracture Critical	6.3
Mobility	**8.6**
Detour Length	1.0
ADT	1.3
Primary	1.0
Secondary	0.6
Interstate	1.6
Bridge Posting	1.6
Truck Volume (ADTT)	1.5
Functionality	**11.0**
Deck Geometry Rating	2.5
Vertical Underclearance	5.6
Horiz. Underclearance	2.9
Maintenance Needs	**18.2**
Priority Needs	14.2
Recommended Needs	4.0
Maintenance Burden	**26.8**
Burdensome	9.7
Reoccurring	17.1

Rank	Performance Measure	Weight
1	Reoccurring Maintenance	17.1
2	Priority Needs	14.2
3	Substructure	10.9
4	Burdensome Maintenance	9.7
5	Superstructure	9.5
6	Fracture Critical	6.3
7	Deck	5.6
8	Vertical Underclearance	5.6
9	Recommended Needs	4.0
10	Scour	3.0
11	Horiz. Underclearance	2.9
12	Deck Geometry Rating	2.5
13	Bridge Posting	1.6
14	Interstate	1.6
15	Truck Volume (ADTT)	1.5
16	ADT	1.3
17	Detour Length	1.0
18	Primary	1.0
19	Secondary	0.6

3.5 Development of Value Functions

As detailed in the literature review on decision analysis (Section A.5.2), value functions, $V(x)$, map individual performance measures from their respective natural scale to a normalized scale of 0-100. In this way, when the performance measures are combined to develop a composite index, the relative weighting of the performance measures retains its meaning. The simplest mapping that can be used is a linear value function, which uses the form

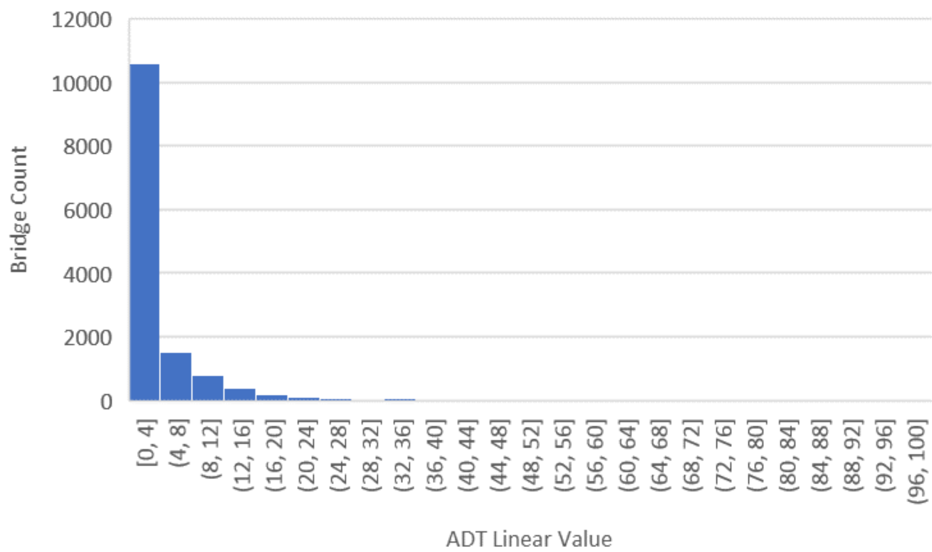
$$V(z) = 100\left(\frac{z - A}{B - A}\right) \tag{3.1}$$

where z is the performance measure on it natural scale and A and B are the minimum and maximum performance measure values observed across the entire bridge inventory. A linear value function assumes that the performance measure is directly proportional to the priority for replacement. For performance measures that have a natural scale where higher numbers on the scale indicate improved performance, such as the condition ratings and appraisals, the value function can be simply inverted so that lower condition ratings or appraisals receive higher scores in the prioritization and higher condition ratings receive lower scores. However, the linear value functions still assume a direct linear relationship between the performance measures and the priority for replacement. Table 3.6 provides a summary of the assumed proportionality of the individual performance measures with the priority for bridge replacement.

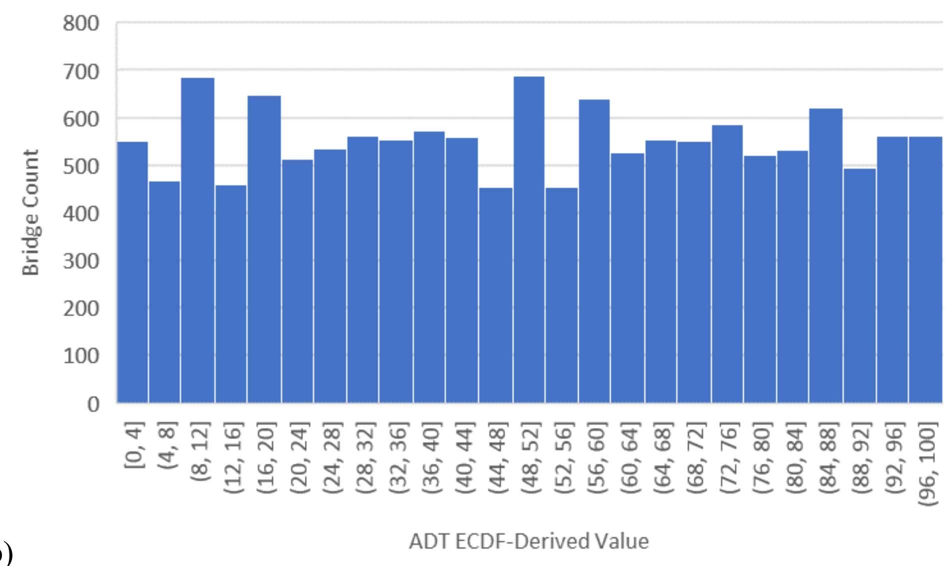
Although linear value functions have been used extensively in decision analysis, including within the NCHRP 590 guidance, there are statistical issues that can arise as a result of their use. For example, if a disproportionate fraction of the bridge inventory has a performance measure that is distributed over a narrow range of the full scale, then there will be clustering of the prioritization scores over a small range. An example of this occurrence is in the ADT performance measure. Since a disproportionately small fraction of the bridge inventory consists of bridges with very high ADT values, the value function scores computed using a linear value function will be clustered with nearly all bridges in the inventory receiving a score of less than 20 for this performance measure (Figure 3.6a). One method to address the statistical issues is to use an empirical cumulative distribution function (ECDF) to develop the value function. An ECDF is the computed statistical cumulative distribution of scores for a particular performance measure. Similar to the linear value functions, the bridge with the highest performance measure value will receive a score of 100 for the particular value function and the bridge with the lowest performance measure value will receive a score of 0. However, the ECDF assigns the scores for all other bridges based on the percentage of bridges with a performance measure value less than or equal to the value for the bridge being scored. By this approach, the ECDF eliminates clustering since it creates a uniform distribution of value function scores across each performance measure. This is demonstrated by application of the ECDF value function for the ADT performance measure applied to all of the bridges in the state inventory (Figure 3.6b). In contrast to the clustering of scores developed with the linear value function, the ECDF distributes the scores across the full range of the performance measure. NCDOT currently uses the ECDF to develop scores for performance measures within the State Transportation Improvement Programs starting with Prioritization 4.0 (NCDOT, 2018). An illustration of the development of linear and ECDF value functions for the substructure condition rating, which is assumed to be inversely proportional to the priority for replacement is presented in Figure 3.7.

Table 3.6. Assumed Proportionality for Bridge Replacement Priority

Performance Measure	**Assumed Proportionality**
ADT	Proportional
ADTT	Proportional
Burdensome Repair and Maintenance	Proportional
Detour Length	Proportional
Fracture Critical	Proportional
Priority Maintenance	Proportional
Recommended Maintenance	Proportional
Reoccurring Burdensome Repairs and Maintenance	Proportional
Bridge Posting	Inversely Proportional
Deck Condition	Inversely Proportional
Deck Geometry Appraisal	Inversely Proportional
Major Rehabilitation Total	Inversely Proportional
Preservation Total	Inversely Proportional
Reoccurring Major Rehabilitation	Inversely Proportional
Reoccurring Preservation	Inversely Proportional
Scour Critical	Inversely Proportional
Substructure Condition	Inversely Proportional
Superstructure Condition	Inversely Proportional
Underclearance Appraisal	Inversely Proportional



a)



b)

Figure 3.6. Distribution of value function scores for ADT performance measure applied to NCDOT bridge inventory with a) linear value function, b) ECDF value function

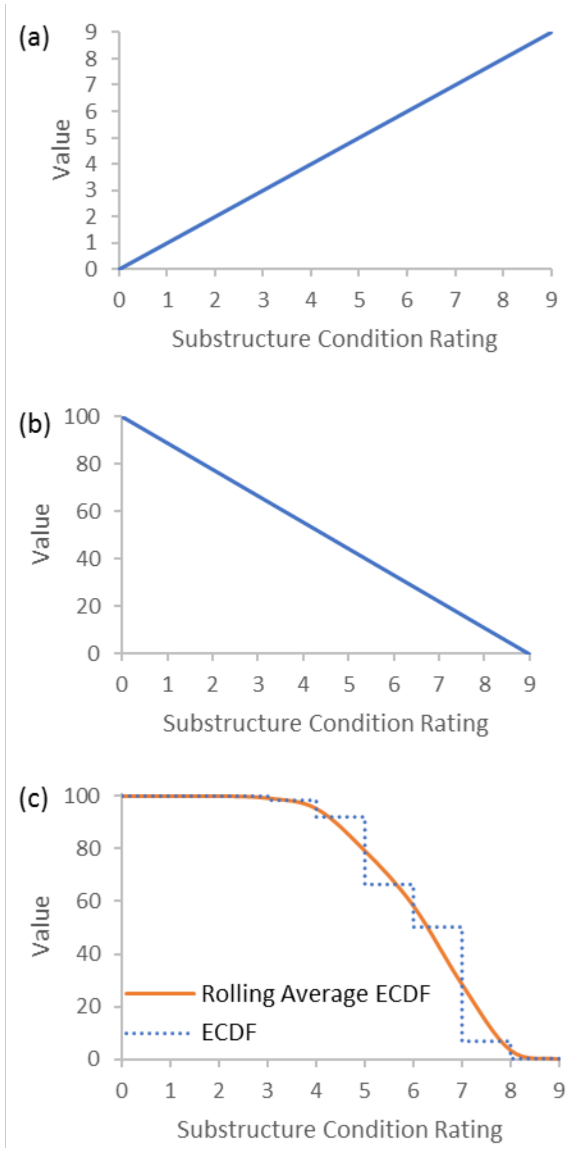


Figure 3.7. Illustration of linear and ECDF value functions developed for substructure condition rating performance measure: a) raw performance measure rating scale; b) linear value function; c) ECDF value function

The raw data used to develop a centralized database for statistical analysis were sourced from the BMS Network Master, the National Bridge Inventory (NBI) ASCII file, the Inspector Recommended Maintenance Needs database housed in the BMS, and the Maintenance Management System (MMS) history. The Network Master contains most of the items necessary to compute the proposed set of performance measures outside of the maintenance need and maintenance burden criteria. The exceptions are the ADTT, fracture criticality, and bridge posting appraisal, which needed to be sourced from the NBI file. As previously detailed in the discussion of the revised set of performance criteria and measures, the Inspector Recommended Maintenance Needs database was used to compute the total cost of priority maintenance needs and total cost of recommended maintenance needs for each structure under the maintenance needs criterion.

Likewise, the MMS history was used to compute the total cost of burdensome repairs and maintenance, total cost of major rehabilitation investments, total cost of preservation actions, total cost of reoccurring burdensome repairs and maintenance, total cost of reoccurring major rehabilitation investments, and total cost of reoccurring preservation actions for each bridge in the inventory. The Network Master and Inspector Recommended Maintenance Needs databases provides a snapshot of the entire state inventory of structures at the current instant in time and, unlike historical databases, are routinely updated with new inspection data. For the research performed in this study, all of the databases used to produce the final analyses were sourced concurrently in July of 2016.

While most of the conventional performance measures could be mapped to value functions directly, the scour vulnerability appraisal required preprocessing prior to the development of the value functions. The scour vulnerability rating scale is prescribed by the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (FHWA, 1995). This scale ranges from 0 to 9 where higher ratings reflect a lower structural risk due to scour, but the rating also includes non-numerical codes for bridges not over water, over an unknown foundation, or over tidal water and not evaluated for scour. In order to use the scour ratings to reflect vulnerability, the non-numerical ratings were converted to numerical values and ratings were reassigned to a new scale to better reflect the severity of scour potential. In this reassignment of ratings, bridges not evaluated for scour were assumed to carry a higher potential vulnerability to scour than bridges that have been determined to be stable for scour conditions and bridges not subject to scour. The adjusted scour critical codes are summarized in Table 3.7.

Table 3.7: Translation of Scour Appraisals to Numeric Scale

NBI Code	**Reassigned Scale**	**Description**
N	7	Bridge not over a waterway
9, 8, 5	6	Bridge foundations stable for calculated scour conditions
U, T, 6	5	Bridge not evaluated for scour
4	4	Same as NBI description
3	3	Same as NBI description
2	2	Same as NBI description
1	1	Same as NBI description
0	0	Same as NBI description

When preparing the value functions, it was discovered that the vertical underclearance and horizontal underclearance appraisals are not directly available in either the BMS or the NBI databases. The Recording and Coding Guide for the Appraisal of the Nation's Bridge Inventory (FHWA, 1995) explains that the lower of the vertical underclearance and horizontal underclearance appraisal values are taken as the Item 69 – Underclearances, Vertical and Horizontal appraisal. While the individual vertical underclearance and horizontal underclearance values can be calculated, they are case dependent on the functional classification and directionality of traffic of the underpassing route. For simplicity and to ease implementation within the BMS, value functions were developed using the general critical underclearance appraisal already recorded in the BMS and NBI, rather than for the vertical and horizontal underclearances separately. Based on the very low overall relative weights assigned to the vertical and horizontal underclearance appraisals within the practitioner survey, this simplified approach is justified and is not expected to significantly influence the new priority replacement index or statistical assessment of the classification accuracy.

With respect to the maintenance need and maintenance burden performance measures, it was unknown whether the costs within each performance measures should be calculated as total costs or if the costs should be normalized relative to the estimated replacement cost. If total costs are used, then the performance measures reflect the absolute scale of the needs and burdens, which would emphasize larger and more costly bridges in the prioritization. Alternatively, by dividing the total costs by the estimated replacement cost, the relative scale of the maintenance needs and maintenance burden would be normalized to the size of the structure to potentially alleviate the emphasis of either smaller or larger structures in the prioritization. In this research, the estimated replacement costs were sourced from the BMS. These values are calculated using the deck area and fixed values for unit costs based only on route type. All of the value functions computed for each performance measure using the databased records are presented in Appendix D.

3.6 Development of Statistical Models for Prioritization of Bridge Replacements

The practitioner survey conducted in this research relies on the ability of experts to fully understand the tradeoffs between a large number of performance measures and accurately assess their preference and risk attitudes throughout the survey. As an alternative to this challenging process, the research team explored the use of statistical regression to understand the preference and risk attitudes being applied currently to the selection of bridge replacement projects. In other words, if it is assumed that the current list of active and scheduled bridge project reflects the priorities, preferences, and risk attitudes of the NCDOT since it was developed using the existing decision making process, then statistical analysis of the factors associated with a greater probability of a bridge being selected for replacement can produce a data-driven alternative to the surveying process. In this research effort, two statistical regression techniques, binary logistic regression and constrained regression on an additive utility function using a genetic algorithm, were employed to produce prediction models to classify bridges as either likely to be selected for replacement or unlikely to be selected for replacement. As previously detailed, the research team was provided a list of all active and scheduled bridge replacement projects, but this list does not reflect the relative priority of individual projects. Consequently, the statistical regressions performed are constrained to a classification problem where the response variable is the binary outcome of either being selected for replacement or not being selected for replacement. A multicollinearity check was performed on each set of value functions ahead of all statistical regression to ensure that no value functions expressed collinearity. Based on the multicollinearity check, the performance measure for truck traffic was recalculated using the percent ADTT to alleviate a collinearity issue with the ADT performance measure. Additional statistical regression techniques, including constrained linear least squares regression, were also evaluated, but results for these statistical models are not presented in this final report because the classification accuracy of these models was not as strong as for the model presented herein. Information on the constrained linear least squares regression and assessment of the performance of the regression models can be found in a Master of Science thesis prepared by one of the graduate research assistants that worked on this effort (Alar, 2018).

3.6.1 Binary Logistic Regression

Logistic regression is a statistical method for performing regression on responses that are binary or dichotomous (Hosmer et al., 2013). From an application perspective, one of the benefits of logistic regression is that the developed regression model can be used to assess the probability of the response classification. In other words, from the perspective of this research, a logistic regression model offers the ability to predict the probability that a bridge would be selected for replacement. The probability can be interpreted as a measure of priority. As identified in the literature review (and discussed in Section A.6), logistic regression has been used in several research efforts focused on prioritization of infrastructure replacement and rehabilitation projects. Logistic regression can be extended to nominal responses, where more than two outcomes are possible, as well as ordinal responses, where there is a hierarchy among the outcomes. Such techniques would permit an interesting extension of the work presented in this report to classification of rehabilitation and preservation priorities, in addition to replacement priority. However, data on rehabilitation and preservation actions were not sufficiently available in this study to permit nominal logistic regression, so binary logistic regression was only performed on the replacement status. It is notable that binary logistic regression has been found to be preferable to other forms of logistic regression when applied to infrastructure projects (Salman and Salem, 2012).

Binary logistic regression transforms the function for the response so that it is constrained to fall within the range of 0 to 1 consistent with binary classification. It does this through the logit function, which is the natural logarithm of the odds, also known as the log-odds. The odds of an event occurring is the ratio of the probability that the event will occur to the probability that the event does not occur. Since binary responses have only two possible outcomes, if the probability that an event occurs is $p(x)$, then the probability that an event will not occur is $(1 - p(x))$. Therefore the odds of a bridge being selected for replacement is

$$Odds = \frac{p(x)}{1 - p(x)} = \frac{Probability\ that\ bridge\ will\ be\ selected\ for\ replacement}{Probability\ that\ bridge\ will\ not\ be\ selected\ for\ replacement} \tag{3.2}$$

Odds ranges from 0 (i.e. event is guaranteed to never occur) to infinity (event is guaranteed to always occur). An odds of 1 (or 1:1) indicates a 50% probability, as there would be an equal probability of the event occurring and not occurring. Table 3.8 summarizes the relationship between odds and probability.

Table 3.8: Relationship between Odds and Probability

Odds (decimal)	Odds (fraction)	Probability
0	0:1	0%
0.11	1:9	10%
0.25	1:4	20%
0.43	3:7	30%
0.67	2:3	40%
1	1:1	50%
1.5	3:2	60%
2.33	7:3	70%
4	4:1	80%
9	9:1	90%
∞	∞:1	100%

The log-odds is used to form a multilinear regression function:

$$\log\frac{p(x)}{1-p(x)} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \tag{3.3}$$

where β_j and x_j are the regression coefficients of the model and the independent variables, respectively (Hosmer et al., 2013). With the logit transformation, the model is still linear with respect to the independent variables and regression coefficients. Once the model is fit to the data to determine the regression coefficients, the probability of the event occurring (in this case, the probability that a bridge will be selected for replacement) can be determined as

$$p(x) = \frac{e^{\beta_0+\beta_1 x_1+\cdots+\beta_n x_n}}{1+e^{\beta_0+\beta_1 x_1+\cdots+\beta_n x_n}} \tag{3.4}$$

Binary logistic regression was performed using the Minitab statistical software package. The regression coefficients were calculated using the Maximum Likelihood Estimator. All of the performance measures were included in the statistical regression with each performance measure treated as a continuous variable over the scale of their respective value function, with the exception of the fracture criticality and system classification performance measures, which were treated as categorical variables using reference cell coding. In developing the regression models, best subset selection using a backward stepwise elimination process was used to reduce each model to only the performance measures found to be statistically significant. This backward elimination is an iterative process that began by performing the regression on the response variable with all of the performance measures and then identifying the predictor variable, or performance measure, with the least statistical significance and removing it from the model. The probability value, or p-value, that tests the null hypothesis was used to identify insignificant performance measures and a p-value threshold of 0.05 was used within the best subset selection process.

Binary logistic regression models were developed for each of the proposed functional forms of the value functions (ECDF and linear) as well as each proposed approach for calculating cost within the maintenance performance measures (total costs or costs relative to the replacement cost). Table 3.9 provides odds ratios for each of the performance measures, as derived from the regression coefficients of the four binary logistic regression models. The reason for presenting the results of the logistic regression as odds ratios rather than regression coefficients is that the odds ratios directly quantify the impact of each performance measure on the overall odds of bridge replacement. The odds ratio for each performance measure indicates the proportional change in odds for a unit change in the value function associated with the performance measure. For example, the odds ratio of 1.044 for substructure condition rating means that the odds of replacement increase by 4.4% for every unit change in the value function. Odds ratios less than 1 indicate that the performance measure was found to decrease the probability of replacement. The farther the odds ratio is from one, the more significant the performance measure was found to be with respect to replacement. Substructure condition rating, superstructure condition rating, deck geometry appraisal, and bridge posting were found to have the most significant odds ratios across the four different logistic regression models. The deck condition rating, fracture critical vulnerability, and underclearance appraisal were not found to be significant in any of the regression models. While not all of the performance measures were retained in the best subset selection process, at least one performance measure within each performance criteria was retained.

Regression models developed using the ECDF value functions expressed nearly identical odds ratios for each performance measure, which indicates that there is no significant effect of expressing the maintenance need and maintenance burden performance measures as cost relative to the estimated replacement costs instead of total costs. For the regression models developed with the linear value functions, the odds ratios for all performance measures outside of the maintenance needs and maintenance burden performance criteria were consistent, but there were significant differences in the odds ratios for the maintenance needs and maintenance burden performance measures. In the binary logistic regression, major rehabilitation investments, preservation actions, reoccurring major rehabilitation investments and reoccurring preservation actions were included in the statistical analysis to explore their significance. Only preservation was found to be mildly significant when the ECDF value functions were used, but this finding should be questioned since the magnitude of the odds ratio suggests that increased preservation actions lead to a mild increase in the priority for replacement. When linear value functions were used, major rehabilitation investments were found to be the most significant predictor of replacement for the model developed using costs relative to the estimated replacement cost. Since the value function for major rehabilitation investments was developed inversely proportional to costs, the odds ratio for this measure predicts that bridges that have received little to no investments in major rehabilitation are more likely to be replaced.

Table 3.9. Summary of Odds Ratios for Performance Measures in Binary Logistic Regression Models

Performance Measure	ECDF Total Cost	ECDF Relative Cost	Linear Total Cost	Linear Relative Cost
Infrastructure Condition				
Substructure Condition	1.044	1.044	1.062	1.063
Superstructure Condition	1.016	1.016	1.036	1.037
Vulnerability				
Scour Criticality	1.007	1.007	1.008	1.009
Mobility				
Bridge Posting	1.012	1.012	1.011	1.011
ADT	1.005	1.005	0.958	0.960
ADTT	1.006	1.006	1.011	1.011
Detour Length	N/A	N/A	0.994	0.994
Secondary Route	1.004	1.003	1.004	1.003
Interstate Route	0.993	0.993	0.991	0.991
Functionality				
Deck Geometry	1.012	1.012	1.024	1.024
Maintenance Needs				
Priority Maintenance	1.003	1.003	N/A	N/A
Recommended Maintenance	1.005	1.005	N/A	N/A
Maintenance Burden				
Burdensome Maintenance	1.004	1.004	1.019	0.980
Reoccurring Maintenance	1.003	1.003	N/A	1.035
Major Rehabilitation	N/A	N/A	N/A	1.064
Preservation	0.998	0.998	N/A	N/A

Since the raw value of each performance measure is mapped to the value function scale, the individual value functions must be used to determine the effect of a unit change in a performance measure on the odds of replacement. For instance, a decrease in substructure condition rating from 7 to 6 would result in a change in value of $\Delta V = 29.8$ according to the ECDF value function for substructure rating (Figure 3.8). Assuming that the other performance measures are unchanged for a particular structure, the new odds of can be calculated using

$$New\ Odds = Old\ Odds * (Odds\ Ratio^{\Delta V}) \tag{3.5}$$

For example, suppose that the probability of replacement for a structure is 10.0%, which corresponds to an odds of 0.111. If the substructure condition rating decreases from 7 to 6 and all other performance measures remain unchanged, the new odds of replacement would be:

$$New\ Odds = 0.111 * (1.044^{29.8}) = 0.40$$

In other words, this change in condition rating would increase the odds of replacement by $(1.044)^{29.8}$ or approximately 360%. This percentage increase in odds of replacement would be the same for any bridge experiencing a change in substructure condition rating from 7 to 6 regardless of the original probability of odds associated with the structure. The new probability of replacement could be calculated as

$$p(x) = \frac{Odds}{1 + Odds} = \frac{0.40}{1 + 0.40} = 0.286 \; or \; 28.6\%$$

Since the ECDF value functions are nonlinear, it is important to note that the change in the odds of replacement with changes in condition ratings is dependent on the initial condition rating. For example, consider another scenario where a bridge undergoes a change in condition rating from 5 to 4. Since the associated change in value according to the value function is 16.0, this change in condition rating would only increase the odds of replacement by $(1.044)^{16.0}$ or approximately 200%. Thus, while the substructure condition rating changed by one in each scenario, the change in the value function was different so the relative change in odds was also different. When linear value functions are used, the effect of changes in performance measures on the odds is uniform across the range of the performance measure.

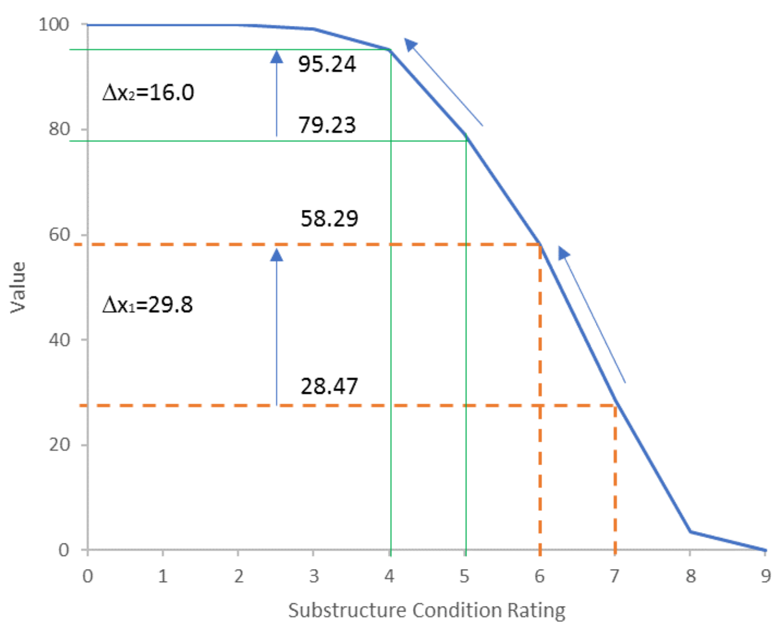


Figure 3.8. Illustration of value function changes for substructure condition ratings

The direct relationship between value changes and odds ratios can be expanded to include multiple performance measures using the general equation

$$New\ Odds = (Old\ Odds)\prod_{i=1}^{n}(Odds\ Ratio_i)^{\Delta V_i}$$

(3.6)

where $Odds\ Ratio_i$ is the odds ratio for an individual performance measure (sourced from Table 3.9) and ΔV_i is the change in value for the performance measure. For example, consider the prior bridge that had a 10% probability of replacement, or 0.111 odds, and experienced a change in substructure condition rating from 7 to 6, which corresponds to a change of 29.8 on the ECDF value function. If there was an increase in ADT from 1,000 to 10,000 (or if this structure was being compared to an identical structure with a higher ADT), there would be an associated change in value for the ADT performance measure of 36.43, as illustrated in Figure 3.9. The net increase in odds with both the change in substructure rating and ADT would be $(1.044)^{29.8}(1.005)^{36.43} =$ 4.33 or 433%. Consequently, the new odds of replacement would be 0.111*4.33 = 0.481, which corresponds to a probability of replacement of 32.5%. Since the original odds of replacement for this hypothetical structure is low, even this large percentage increase in odds does not result in this structure being classified as a likely candidate for replacement.

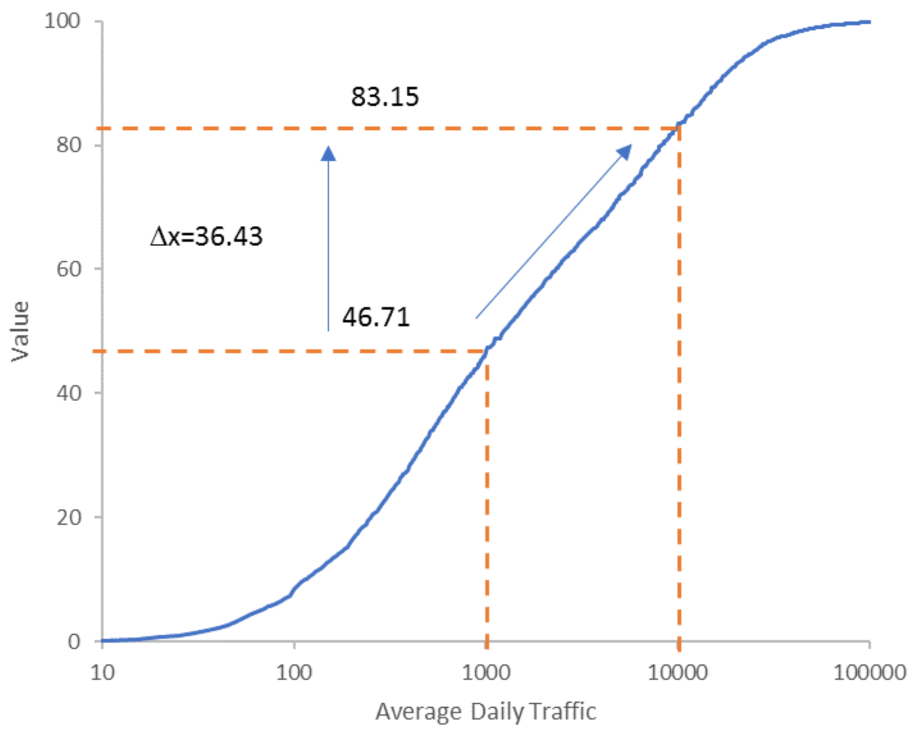


Figure 3.9. Illustration of value function change for ADT

Model summary statistics, including the R^2 and adjusted R^2, for each of the binary logistic regression models are shown in Table 3.10. The R^2 statistic quantifies how well a model fits a given set of data, while the adjusted R^2 includes a penalty for the inclusion of more predictor variables in the model. The regression model developed using ECDF value functions with the maintenance needs and maintenance burden performance measures calculated using total costs was found to produce the best fit to the response data according to both of these measures. The predictive capabilities of each of the statistical models, as well as the practitioner-derived models, will be examined in the next section.

Table 3.10: Summary of binary logistic regression statistics

	ECDF Total Costs	**ECDF Relative Costs**	**Linear Total Costs**	**Linear Relative Costs**
Deviance R^2	0.3285	0.3282	0.3207	0.3232
Deviance Adjusted R^2	0.3268	0.3265	0.3194	0.3217

3.6.2 Regression of Additive Utility Functions with Genetic Algorithm

The binary logistic regression models developed in the prior subsection utilize a model that is appropriate for regression on a binary response variable, but the use of the logit function results in regression coefficients that express the significance of performance measures in terms of odds ratios rather than relative weights. While the binary logistic regression provides the advantage of predicting the probability that a bridge will be selected for replacement, there was a desire to develop statistical models that would attempt to directly identify relative weights for an additive utility function. In other words, statistical models were generated to develop a formula for the priority replacement index that would take the form

$$Priority\ Score(\boldsymbol{x}) = \sum_{i=1}^{n} \beta_i V_i(\boldsymbol{x}) = \beta_1 V_1(x_1) + \beta_2 V_2(x_2) + \cdots + \beta_n V_n(x_n) \tag{3.7}$$

Where β_i and $V_i(x_i)$ are the relative weight and value function score evaluated for the i^{th} performance measure. Since the actual priority score for each structure is unknown, conventional linear regression cannot be applied to this problem.

Since the response data available for regression is the binary classification of whether a bridge has been selected for replacement or not, the objective of the statistical regression could be formulated to maximize the ability of the developed model to discriminate between bridges selected for replacement and bridge not selected for replacement. Both the practitioner-derived and statistically-derived models developed in this study produce a score for each bridge on a scale of 0-100, so classifying a bridge as either a bridge selected for replacement or a bridge not selected for replacement requires that a threshold score be established. At this threshold, any bridges receiving a lower score would be classified by the model as not selected for replacement and any bridges receiving a higher score would be classified as selected for replacement. Establishing the threshold involves a trade-off between the rate of true positive classifications and the rate of false positive classifications. For instance, if the threshold is set very low, then the index will correctly identify most if not all of the bridges selected for replacement as bridges selected for replacement. However, with such a low threshold, it will also incorrectly identify a large number of bridges not selected for replacement as bridges selected for replacement. In other words, with a low threshold there will be a large number of "false alarm" identification of replacement bridges that are not actually in need of replacement, which increases the burden on practitioners to manually evaluate lists of candidate replacement structures. Conversely, if the threshold is set high, then the index may correctly identify no bridges that are not selected for replacement as bridges selected for replacement. However, a large threshold will fail to correctly identify a large percentage of the bridges actually selected for replacement as bridges selected for replacement.

A common approach for assessing the ability of a binary classifier to discriminate between two scenarios is based on the Receiver Operating Characteristic (ROC) curve (Fawcett, 2006). The ROC plots the true positive rate against the false positive rate across all possible values for the threshold. In the context of this research, the true positive rate is the fraction of bridges currently selected for replacement that are correctly identified by the model as being selected for replacement over the total number of bridges currently selected for replacement. The true positive rate is the same as the sensitivity of the model. The false positive rate is the fraction of bridges not currently selected for replacement that are incorrectly identified by the model as being selected for replacement over the total number of bridges not selected for replacement. The false positive rate is equivalent to 1-Specificity. An example of an ROC curve is shown in Figure 3.10. As shown in this illustrative figure, a completely random classifier without any ability to distinguish between two scenarios would fall on the 45 degree diagonal. In contrast, a perfect model would allow for establishing a threshold at which the true positive rate would be 100% and the false positive rate would be 0%. This point in the plot would be the upper leftmost corner. A ROC curve for a prediction model will fall between the random classifier and the perfect classifier. The closer the ROC curve is to the upper leftmost corner, the stronger the model is at distinguishing the binary scenarios, as such a model would be able to simultaneously achieve high sensitivity and high specificity (or high true positive rates and low false positive rates). The Area Under the Curve (AUC), which is the total area under the ROC curve and can be calculated through numerical integration, is often used as a performance metric to evaluate different classification models (Fawcett, 2006). Since the axes of the ROC curve are normalized, the AUC ranges from 0.5 (no ability to discriminate) to 1.0 (perfect ability to discriminate). In the context of this research, the AUC corresponds to the probability that the model will rank any randomly selected bridge that is currently selected for replacement with a higher priority score than any randomly selected bridge that is not currently selected for replacement.

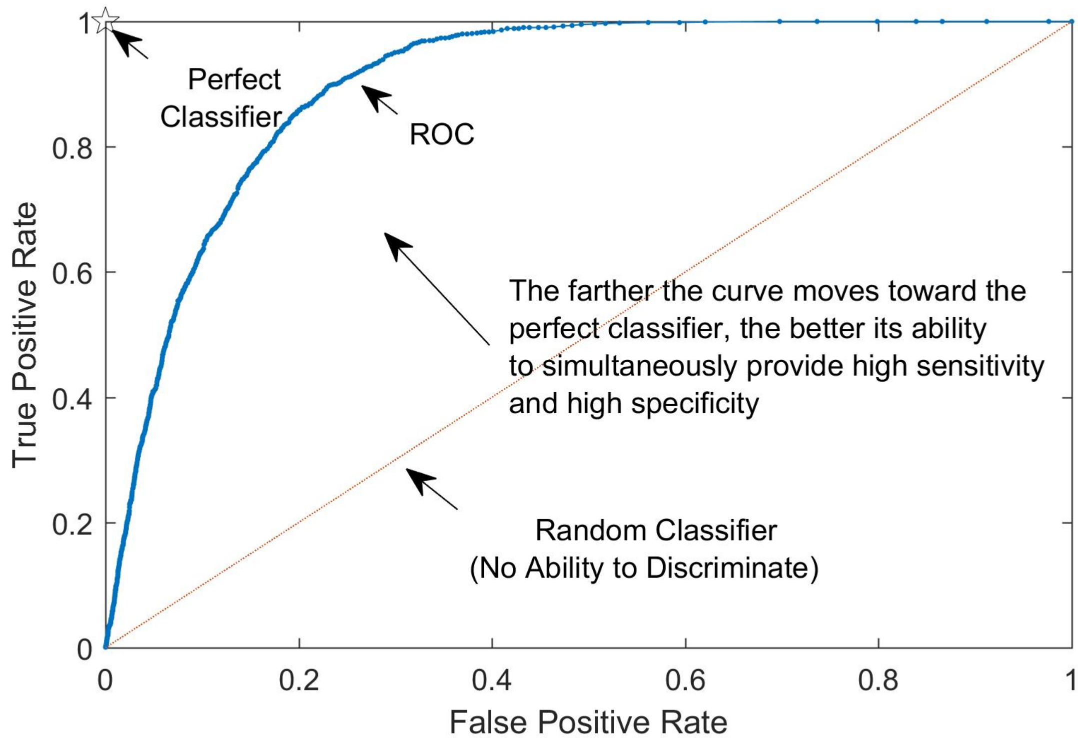


Figure 3.10. An example of a ROC curve

Since the objective of the statistical model is to maximize the ability of the prediction to identify bridges selected for replacement, an optimization was performed to determine regression coefficients for the additive form of the utility function in Equation 3.7 that would maximize the AUC. Since this regression model is not a generalized linear model, a genetic algorithm was used to arrive at the regression coefficients, or relative weights, associated with each performance measure. To ensure that the relative weights summed to 1 (or 100%), a linear equality constraint was enforced in the genetic algorithm. Mathematically, the optimization problem can be stated as:

$$\text{maximize } AUC(\boldsymbol{\beta}) \quad subject\ to \quad \sum_{i=1}^{n} \beta_i = 1 \tag{3.8}$$

The MATLAB computing environment was used to implement the genetic algorithm using the Global Optimization Toolbox. For each optimization, a population size of 400 individuals was used with 5% elite individuals, an 80% crossover rate, and 15% mutation rate. The genetic algorithm was run for approximately 200 generations or until the convergence was reached according to the default stopping criteria established by the toolbox.

As with the binary logistic regression, additive utility function models were developed for each of the proposed functional forms of the value functions (ECDF and linear) as well as each proposed approach for calculating cost within the maintenance performance measures (total costs or costs relative to the replacement cost). Table 3.11 presents a summary of the relative weights derived for the performance criteria and performance measures that result in the best discrimination amongst bridges selected for replacement and bridges not selected for replacement. All of the statistical regressions found that the substructure condition rating was the most important performance measure for distinguishing bridges selected for replacement, with this single performance measure receiving over 25% of the weighting across all models. For models using the ECDF value functions, the bridge posting was the second most significant factor, while for models developed using linear value functions the superstructure condition rating was the second most significant factor. The greater weighting of the superstructure condition rating in the models with the linear value functions was consistent with the findings of the binary logistic regression. In general, the models developed with the ECDF value functions produced consistent relative weights for the set of performance measures, with the most significant change in relative weights between each model occurring for the maintenance needs performance criteria. Similar observations can be made for the models developed with the linear value functions. Since this consistency between models developed using maintenance needs and maintenance burden performance measures computed with total costs and model developed with these performance measures computed with costs relative to the estimated replacement structure were also observed in the binary logistic regression, it is likely that there is not a significant difference in the prioritization if the value functions for these maintenance performance measures are calculated in either way.

Table 3.11. Summary of Relative Weights for Performance Measures and Criteria Obtained from Regression of Additive Utility Function

Criteria or Measure	ECDF Total Costs	ECDF Relative Costs	Linear Total Costs	Linear Relative Costs
Infrastructure Condition	**38.6**	**36.1**	**50.0**	**48.1**
Deck	2.9	1.2	6.6	3.5
Superstructure	8.5	6.5	15.6	18.5
Substructure	27.2	28.4	27.8	26.1
Vulnerability	**8.2**	**9.2**	**8.7**	**7.9**
Scour	5.1	5.0	6.1	5.0
Fracture Critical	3.1	4.2	2.6	2.9
Mobility	**32.8**	**30.5**	**20.9**	**21.2**
Detour Length	3.2	3.2	1.5	0.7
ADT	3.8	3.1	2.2	1.8
Primary	4.0	2.3	2.0	3.6
Secondary	6.0	3.6	3.8	5.4
Interstate	1.7	3.4	1.1	3.0
Bridge Posting	10.4	9.5	6.1	5.0
Truck Volume (ADTT)	3.7	5.4	4.2	1.7
Functionality	**7.6**	**8.4**	**9.9**	**7.7**
Deck Geometry Rating	6.4	5.8	8.7	4.9
Underclearance Appraisal	1.2	2.6	1.2	2.8
Maintenance Needs	**6.0**	**9.3**	**3.6**	**6.2**
Priority Needs	4.1	3.6	0.9	3.4
Recommended Needs	1.9	5.7	2.7	2.8
Maintenance Burden	**6.8**	**6.5**	**6.9**	**8.9**
Burdensome	3.8	3.1	3.5	4.9
Reoccurring	3.0	3.4	3.4	4.0

One of the advantages of performing statistical regressions on the additive utility function is that the relative weighting obtained from the practitioner surveys can be directly compared to relative weights that lead to statistically best discrimination of bridge projects across the bridge inventory. Comparing Table 3.3 to Table 3.11 suggests that practitioner direct weighting may be significantly under-estimating the significance of the mobility performance criteria, slightly under-estimating the significance of the infrastructure condition ratings, and over-estimating the significance of maintenance needs, maintenance burden, and vulnerability performance criteria. Similarly, comparison of Table 3.5 to Table 3.11 suggests that the analytic hierarchy process comparisons completed by the practitioners also under-estimated the significance of the mobility and infrastructure condition performance criteria, while over-estimating the significance of maintenance needs and maintenance burden criteria.

4. Findings and Conclusions

To assess the performance of each of the prioritization models developed from the practitioner surveys and the statistical regressions, several criteria were established based on the objectives of the research. First, the prioritization index must be effective at distinguishing bridges with high priority for replacement from bridges with low priority for replacement. This ability to distinguish bridge projects was assessed by evaluating how well each model classifies all of the bridges in the state inventory using a fixed threshold. Since the distribution of scores varies with each model, a separate threshold was established for each model based on simultaneously maximizing the sensitivity and specificity of the model. This was done by selecting a threshold value that would minimize the distance to the perfect classifier where the true positive rate is 100% and the true negative rate is 0%. An illustration of the point on the ROC curve that establishes the threshold value for each model is shown in Figure 4.1. With the threshold for classification established, the performance of the model was evaluated through the measures for sensitivity, specificity, positive predictive value, negative predictive value, and classification accuracy. All of these statistical measures are specific to the established threshold value. Table 4.1 provides descriptions of each statistical measure applied specifically to the classification of bridges scheduled for replacement.

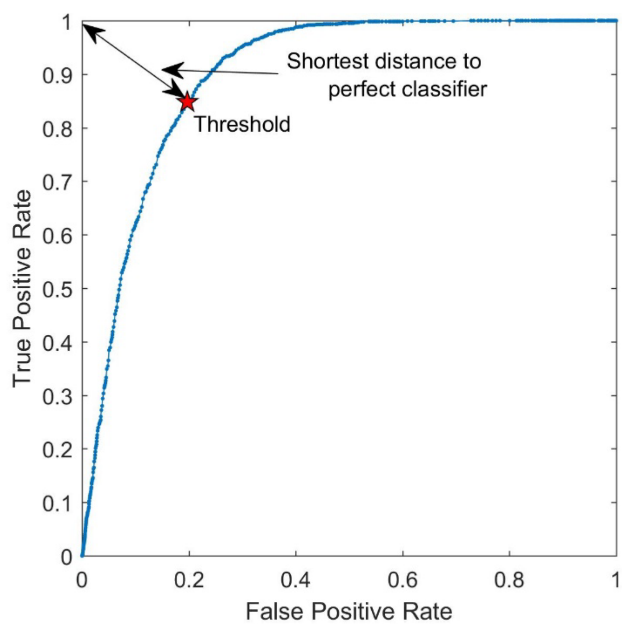


Figure 4.1. Metric used to establish classification threshold for each model

Table 4.1: Summary of Statistical Measures Used to Assess Model Classification Performance When Applied to BMS Data

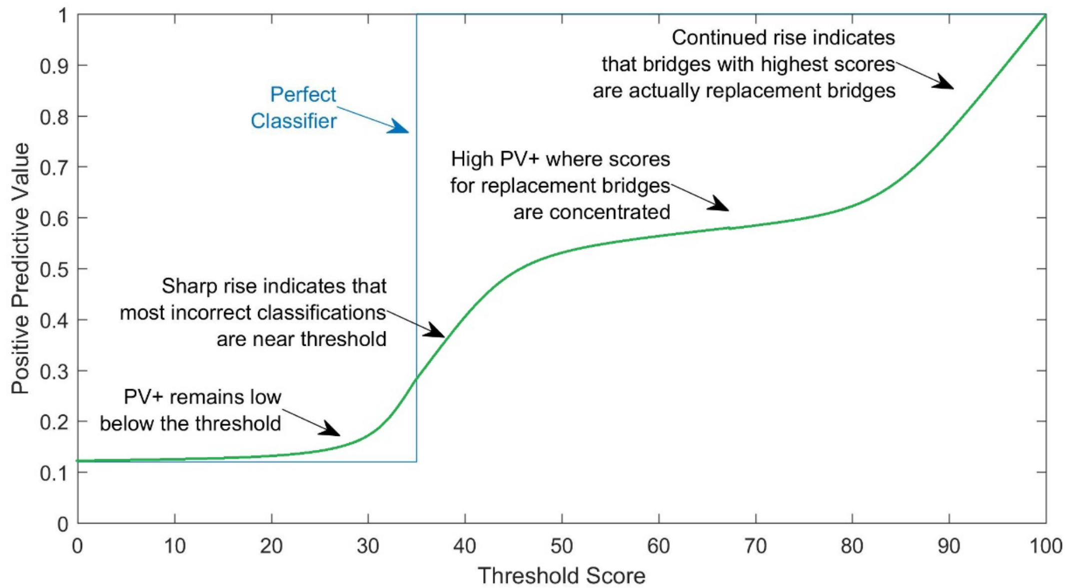
Measure	**Description**
AUC	Probability that a randomly selected bridge scheduled for replacement will be ranked with higher priority than a randomly selected bridge not scheduled for replacement
Sensitivity	Percentage of bridges scheduled for replacement that are correctly classified as scheduled for replacement using the threshold
Specificity	Percentage of bridges not scheduled for replacement that are correctly classified as not scheduled for replacement using the threshold
Positive Predictive Value (PV+)	Percentage of bridges classified using the threshold as scheduled for replacement that are correct classifications
Negative Predictive Value (PV-)	Percentage of bridges not classified using the threshold as scheduled for replacement that are correct classifications
Accuracy	Accuracy of all classifications using the threshold value

It should be acknowledged that some bridges are replaced for reasons that will not be captured by the set of performance criteria and measures developed in this study. For instance, significant redevelopment or investments in other transportation systems, such as rail, may require the replacement of bridges that would not otherwise be selected due to condition, functional deficiencies, or maintenance reasons. Likewise, there are some bridges in the inventory that would be desirable to replace, but have not been selected for replacement due to resource constraints. Also, since the BMS is a dynamic database, there will also be instances of bridges that have new inspection data that will lead to selection for replacement in the near future, but these bridges have not yet been scheduled for replacement and added to the BMIP list. Consequently, while the binary classification of bridges currently selected for replacement and bridges not selected for replacement represents the best data available at the time of this research, the response data is acknowledged to have imperfections and the classification accuracy of the models alone should not be used to produce recommendations for a new priority replacement index. In addition to the ability to distinguish replacement projects from bridges that will not be selected for replacement, the prioritization index should avoid clustering and spread the prioritization scores across the range of the index to allow for better expression of priority. For example, consider an extreme case where a model may perfectly classify bridge replacement projects in the current database using a threshold value of 50. However, if the scores for all of the bridges scheduled for replacement is 51 and the scores for all of the bridges not scheduled for replacement is 49, then this would be a poor index to use in the future because it does not express the relative priority of the individual bridges. To assess the distribution of prioritization scores, histograms were developed for the scores provided to bridges that are not currently scheduled for replacement and those currently scheduled for replacement. Ideally, the scores for bridges not scheduled for replacement should be skewed toward zero, while the scores for bridges currently scheduled for replacement should be distributed across the range of potential scores with minimal evidence of clustering of scores and minimal overlap with the bridges not currently selected for replacement.

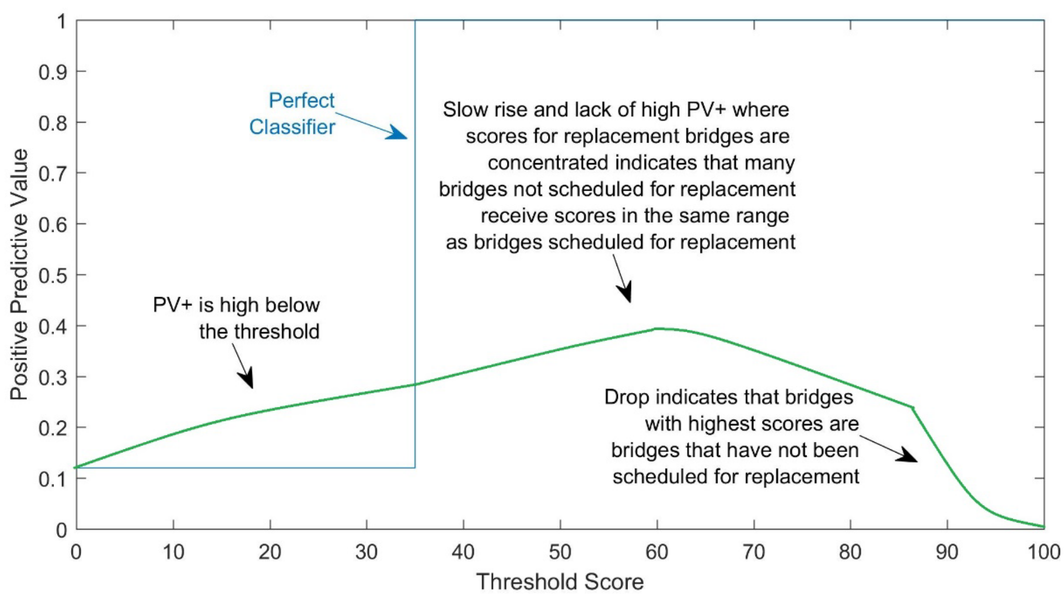
In addition to histograms, the change in positive predictive value with score can be used to provide insight into the relative distribution of score assigned to bridges scheduled for replacement compared to bridges not scheduled for replacement. The positive predictive value for a particular score indicates the percentage of bridges receiving that score or higher that are actually structures scheduled to be replaced. Figure 4.2 graphically presents desirable and undesirable characteristics for the change in positive predictive value beyond the threshold score. If the majority of bridges that are incorrectly classified as structures scheduled to be replaced receive scores close to the threshold score, then the positive predictive value will rise sharply after the threshold and increase to a high percentage. Ideally, this high positive predictive value would remain high through the range of scores where the majority of bridges scheduled for replacement are concentrated. This would reflect that the prioritization score results in a strong ability of the index to separate bridges scheduled for replacement from those not scheduled for replacement in the range where most bridges scheduled for replacement receive scores. Lastly, it is desirable for the positive predictive value to increase to 1 at the high end of the scale, which would indicate that the bridges receiving the highest scores are in fact bridges that have been scheduled for placement. If the positive predictive value decreases at the high end of the scale, then bridges that have not been selected for replacement are being assigned the highest scores in the index.

To illustrate the qualitative assessment of distribution of scores, the histograms and positive predictive values computed for the PRI are presented in Figure 4.3. The threshold value resulting in the best binary classification performance is indicated on each plot with a dashed vertical line. The histograms for the PRI exhibit generally good separation between scores assigned to bridges scheduled for replacement and those not scheduled for replacement, with the exception of a large number of bridges scheduled for replacement receiving low scores (the scores within the mode associated with the first peak of the bimodal distribution). This is reflected in the positive predictive value below the threshold, which remains high relative to the positive predictive value at the threshold. However, the positive predictive value for the PRI does achieve good values in the range where most bridges scheduled for replacement are concentrated (nearly 50%) and the positive predictive value remains high through the upper end of the scale until the last 10% of the scale where it tends toward zero. This indicates that the bridges with the highest current PRI values have not been selected for replacement, which was observed in the review of the PRI in Section 1.1 of this report.

Lastly, the prioritization index should be objective, transparent, avoid double-counting, and incorporate all performance measures that are significant to the decision to prioritize one project over another. With respect to these objectives, the current PRI is not acceptable because the case-specific, nonlinear, and nested formulas obscure the influence of performance measures on the prioritization score, there is significant multiple counting of performance measures throughout the index, and it does not incorporate measures that consider current maintenance needs identified through element level inspection or the frequency and cost of burdensome maintenance that has been recently applied to each bridge. All of the models developed in this research from either the practitioner surveys or the statistical regressions are transparent, count each performance measure only once, and consider conventional performance measures as well as maintenance needs and maintenance burden criteria.

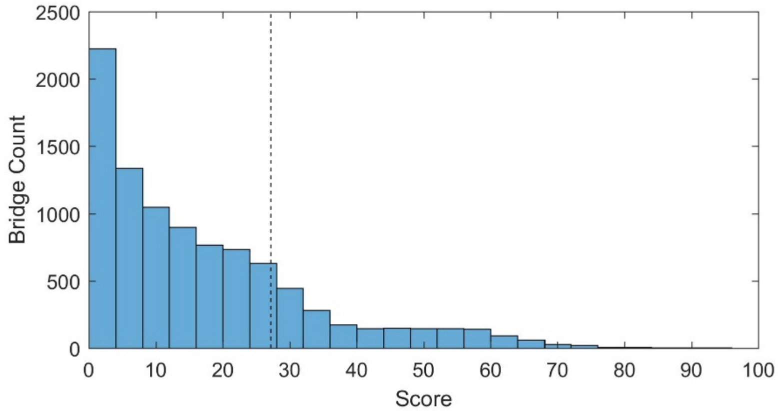


a)

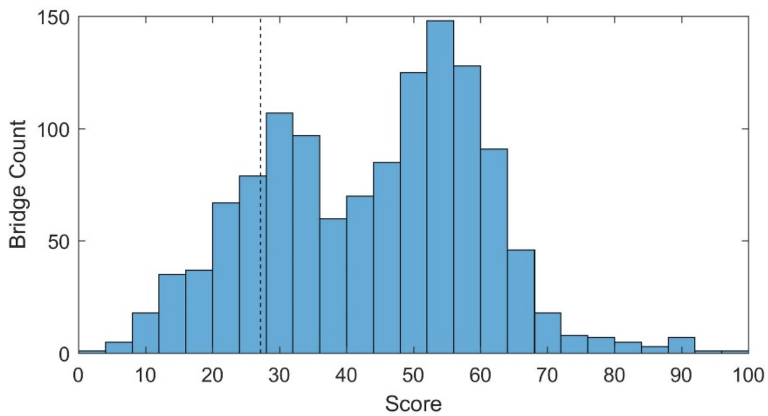


b)

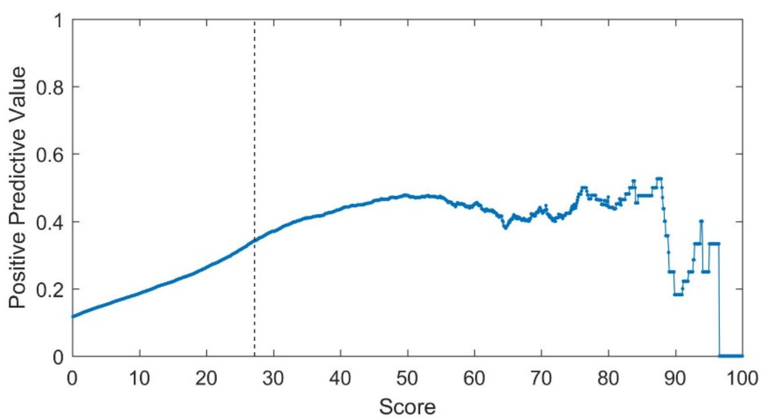
Figure 4.2. Illustration of qualitative assessment of change in positive predictive value with score: a) desirable performance characteristics; b) undesirable performance characteristics



a)



b)



c)

Figure 4.3. Assessment of Priority Replacement Index Scores for North Carolina Bridges: a) histogram of scores for bridges not scheduled for replacement; b) histogram of score for bridges scheduled for replacement; c) positive predictive value as a function of score

4.1 Assessment of Priority Replacement Indices Developed from Survey Results

Table 4.2 and Table 4.3 provide summary classification statistics for the additive utility functions developed through the Direct Weighting and Analytic Hierarchy Process portions of the practitioner survey, respectively. Classification statistics for the current PRI scores are also provided for comparison. Across all of the evaluation metrics, the models developed using the results from the Direct Weighting portion of the survey out-performed the models developed using the results from the Analytic Hierarchy Process portion of the survey. However, the PRI out-performed the practitioner-derived models as a binary classifier of bridges currently selected for replacement. The results indicate that the better classification accuracy of the PRI is driven primarily by the improved positive predictive value. Based on the classification threshold for the PRI identified from the ROC curve, bridges with a PRI score above the classification threshold 27.2 have a 34.2% probability of being a bridge currently scheduled for replacement. The best performing model developed from the surveying process was only able to achieve a positive predictive value of 28.1%. Across the models developed from the surveying process, there was little difference in classification statistics for models developed with the maintenance performance measures computed with total costs and those developed with these measures computed with costs relative to the estimated replacement structure. The model from the surveying process with the best classification performance was developed using Direct Weighting with linear value functions and maintenance performance measures computed with total costs. For models developed using the ECDF value functions, the model developed using Direct Weighting with the performance measures computed with costs relative to the replacement costs was the best performing model.

Table 4.2: Classification Performance of Models Developed by Practitioner Direct Weighting

	PRI	**ECDF Total Costs**	**ECDF Relative Costs**	**Linear Total Costs**	**Linear Relative Costs**
AUC	0.906	0.858	0.869	0.882	0.882
Threshold	27.2	45.1	40.7	24.6	24.9
Sensitivity	82.8%	83.9%	84.2%	85.3%	85.9%
Specificity	84.2%	73.1%	75.1%	78.4%	78.1%
PV+	34.2%	23.6%	25.1%	28.1%	28.0%
PV-	98.0%	97.9%	98.0%	98.2%	98.2%
Accuracy	84.1%	74.1%	75.9%	79.0%	78.8%

Table 4.3: Classification Performance of Models Developed by Practitioner Analytic Hierarchy Process

	PRI	**ECDF Total Costs**	**ECDF Relative Costs**	**Linear Total Costs**	**Linear Relative Costs**
AUC	0.906	0.833	0.827	0.873	0.876
Threshold	27.2	37.2	33.6	21.1	21.2
Sensitivity	82.8%	81.0%	80.5%	85.2%	85.8%
Specificity	84.2%	71.1%	70.3%	76.2%	75.8%
PV+	34.2%	21.8%	21.1%	26.2%	26.0%
PV-	98.0%	97.4%	97.3%	98.1%	98.2%
Accuracy	84.1%	72.0%	71.2%	77.0%	76.7%

As described at the beginning of this section of the report, the suitability of each model should not be based solely on the classification statistics, as these measures do not reflect the distribution of the scores across the range of the prioritization scale or the absence of undesirable clustering of scores. For these considerations, histograms of the scores provided to bridges not currently selected for replacement and bridges currently selected for replacement can be used for assessment. Figure 4.4 presents the ROC curve, histograms of scores, and positive predictive values for the current PRI and the model developed with Direct Weighting, linear value functions, and total maintenance costs, which was the practitioner-derived model with the best classification performance. The histograms for the model developed by the Direct Weighting portion of the survey produce a relatively poor distribution of scores for bridges currently selected for replacement, as the scores are heavily concentrated around 25-30. This clustering of priority scores in a narrow portion of the full range of the index makes it difficult to distinguish the priority of the individual bridges scheduled for replacement against each other. Similar clustering of priority scores within a narrow portion of the 0-100 ranking scale was observed for all of the practitioner-derived models using linear value functions. The positive predictive value over the range of scores where bridges scheduled for replacement are concentrated in the survey model remains low and trends toward zero as the score increases, which further indicates undesirable performance of this particular model.

To investigate the distribution of scores for a model developed with ECDF value functions, the model developed from Direct Weighting with ECDF value functions and maintenance costs computed relative to the estimated replacement costs was analyzed, since this model produced the best classification performance amongst the practitioner-derived models using ECDF value functions. Figure 4.5 presents the ROC curve, histograms of scores, and positive predictive values for this model, with the same quantities shown for the current PRI for comparison. For this model, the scores for bridges currently selected for replacement are better distributed across a greater portion of the prioritization scale. However, the scores for bridges not selected for replacement are widely distributed across the scale with a large number of bridges that receive scores in the same range where the majority of bridges scheduled for replacement are concentrated. This is also reflected in the positive predictive values, which increase very slowly and remain relative low across the range where most scores for bridges scheduled for replacement are concentrated. As with the other survey model, the positive predictive values trend toward zero at the end of the range of the index, which indicates that the bridges receiving the highest scores are actually bridges that have not been scheduled for replacement.

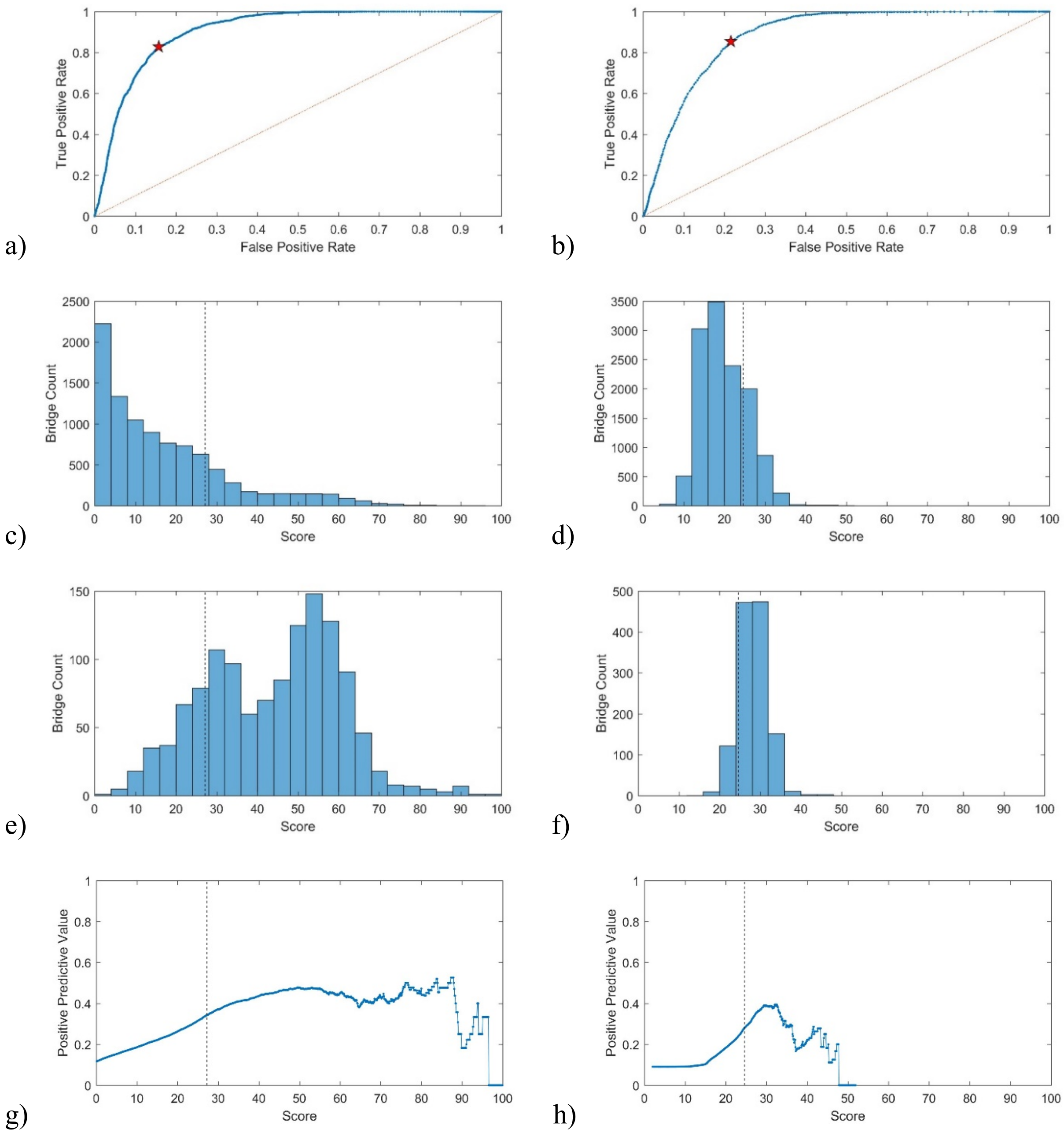


Figure 4.4. Comparison of ROC and distributions of scores for model developed from Direct Weighting with linear value functions and total maintenance costs: a) ROC curve for PRI; b) ROC curve for survey model; c) bridges not selected for replacement PRI scores; d) bridges not selected for replacement scores from survey model; e) bridges selected for replacement PRI scores; f) bridges selected for replacement scores from survey model; g) PV+ for PRI; h) PV+ for survey model

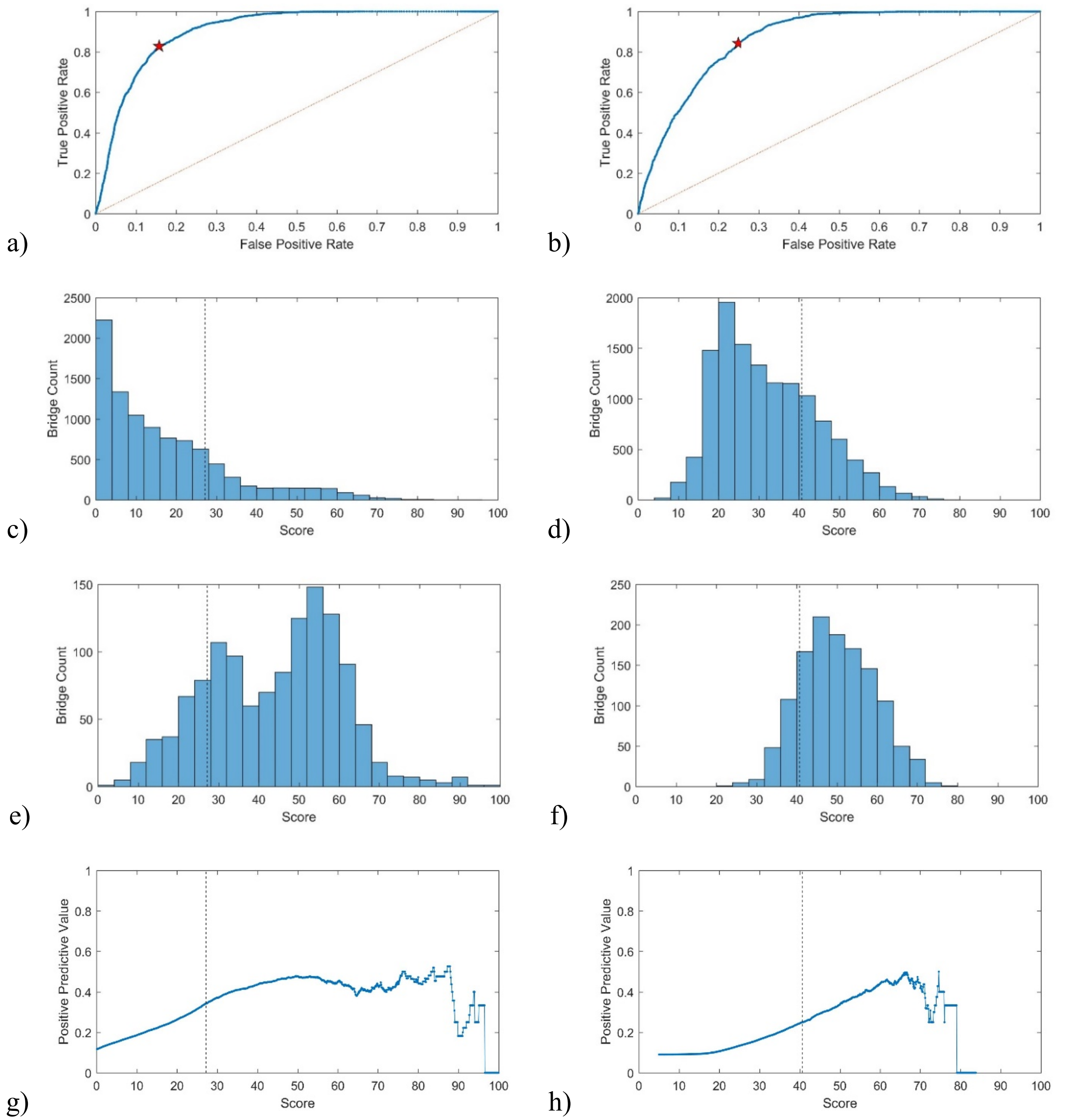


Figure 4.5. Comparison of ROC and distributions of scores for model developed from Direct Weighting with ECDF value functions and maintenance costs computed relative to estimated replacement costs: a) ROC curve for PRI; b) ROC curve for survey model; c) bridges not selected for replacement PRI scores; d) bridges not selected for replacement scores from survey model; e) bridges selected for replacement PRI scores; f) bridges selected for replacement scores from survey model; g) PV+ for PRI; h) PV+ for survey model

4.2 Assessment of Statistical Models

Models developed from statistical regression are expected to achieve better performance as binary classifiers than those developed from the practitioner surveys since the regression techniques develop the relative weights to maximize the classification accuracy subject to the functional form of the regression model. Table 4.4 presents the summary classification statistics for the regression models developed using binary logistic regression along with the classification statistics for the PRI for comparison. The binary logistic regression models were found to achieve AUC values similar to those obtained by the PRI as well as similar, yet slightly lower, classification accuracies. All of the binary logistic regression models out-performed the models derived from the practitioner surveys for all of the statistical measures. As a reminder, the scores produced by the binary logistic regression models equate to a predicted probability that a bridge will be classified for replacement. The statistical analysis reveals that a threshold around 10% probability results in the best classification performance for the binary logistic regression models. Bridges receiving an assigned probability of less than 10% were correctly classified as not scheduled for replacement in greater than 98% of instances. For bridges receiving an assigned probability greater than 10% were actually scheduled for replacement in approximately 30% of all instances. These metrics compare well with the classification performance of the PRI at its ideal threshold of 27.2.

Table 4.4: Classification Performance of Models Developed by Binary Logistic Regression

	PRI	ECDF Total Costs	ECDF Relative Costs	Linear Total Costs	Linear Relative Costs
AUC	0.906	0.895	0.897	0.899	0.900
Threshold	27.2	10.8	11.6	10.5	10.4
Sensitivity	82.8%	85.5%	85.5%	85.7%	85.9%
Specificity	84.2%	79.6%	80.1%	79.9%	80.0%
PV+	34.2%	29.4%	29.9%	29.7%	29.8%
PV-	98.0%	98.2%	98.2%	98.3%	98.3%
Accuracy	84.1%	80.2%	80.6%	80.4%	80.5%

Based on the classification performance metrics, the best performing binary logistic regression model is the one that used the ECDF value functions with maintenance costs expressed relative to the estimated replacement costs. However, the classification performance of all of the binary logistic regression models was extremely similar so selection of the best binary logistic regression model should be based on the distributions of assigned scores and change in positive predictive value with score. Review of these qualitative indicators indicated preference for the binary logistic regression model using the linear value functions computed with total maintenance costs. Figure 4.6 provides the ROC curve, histograms of scores, and positive predictive values for the current PRI and this model. This model performs exceptionally well at assigning very low probabilities for replacement to bridges that are not currently scheduled for replacement, as reflected in the histogram of scores provide to such bridges. The extremely large number of bridges not selected for replacement (>8,000) receiving a score of less than 5 is particularly noteworthy as the binary logistic regression creates clear separation of these structures from others in the inventory that are more likely to be selected for replacement. Also, the score for bridges currently selected for replacement are well distributed across the range of the index above the threshold value and nearly maximize the full scale of the index. Since the index is a probability, it should be recognized that it would be unlikely for any bridge to receive a score of 100 from a binary logistic regression model, because that would indicate absolute certainty that the bridge would be selected for replacement. However, a significant number of bridges do receive prioritization scores that reflect very high probabilities for replacement and come close to maximizing the full scale of the index. Given the large range above the threshold that is utilized by the developed model for bridges selected for replacement, this model avoids clustering and is expected to provide clear distinction in ranking between individual projects. The positive predictive values for the binary logistic regression model also quickly rise to approximately 50% shortly after the threshold value and remain high throughout the utilized range. Furthermore, the positive predictive value increases toward the high end of the scale, which indicates that the bridges receiving the highest scores by this index are in fact bridges that have been currently selected for replacement. This performance across the highest end of index values was unique to the models developed using binary logistic regression and highlights the strength of using this technique to develop the prioritization index. The most notable weakness of the binary logistic regression model evident in the histograms and positive predictive values was the presence of scores below the classification threshold for bridges scheduled for replacement, which lead to a slower drop in positive predictive values below the threshold. However, it should be noted that the magnitude of the threshold can distort these comparisons, as in actuality the binary logistic regression model resulted in only 178 false negatives at its optimized classification threshold, while the PRI results in 215 false negatives.

Based on the similar classification statistics and the improved distributions of assigned scores, the binary logistic model developed using linear value functions with total maintenance costs has been identified as an improvement over the current PRI formula from a performance perspective. Furthermore, this binary logistic regression model is an improvement from the PRI with respect to transparency, inclusion of maintenance performance criteria that are known to affect the decision to prioritize one structure over another, and avoidance of double-counting of performance measures. It should also be recognized that the generation of scores by the binary logistic regression model as probabilities that a bridge will be selected for replacement based on their performance measures is more meaningful than simply ranking on a normalized scale and could facilitate advanced probabilistic approaches to asset management that could be incorporated in the BMS.

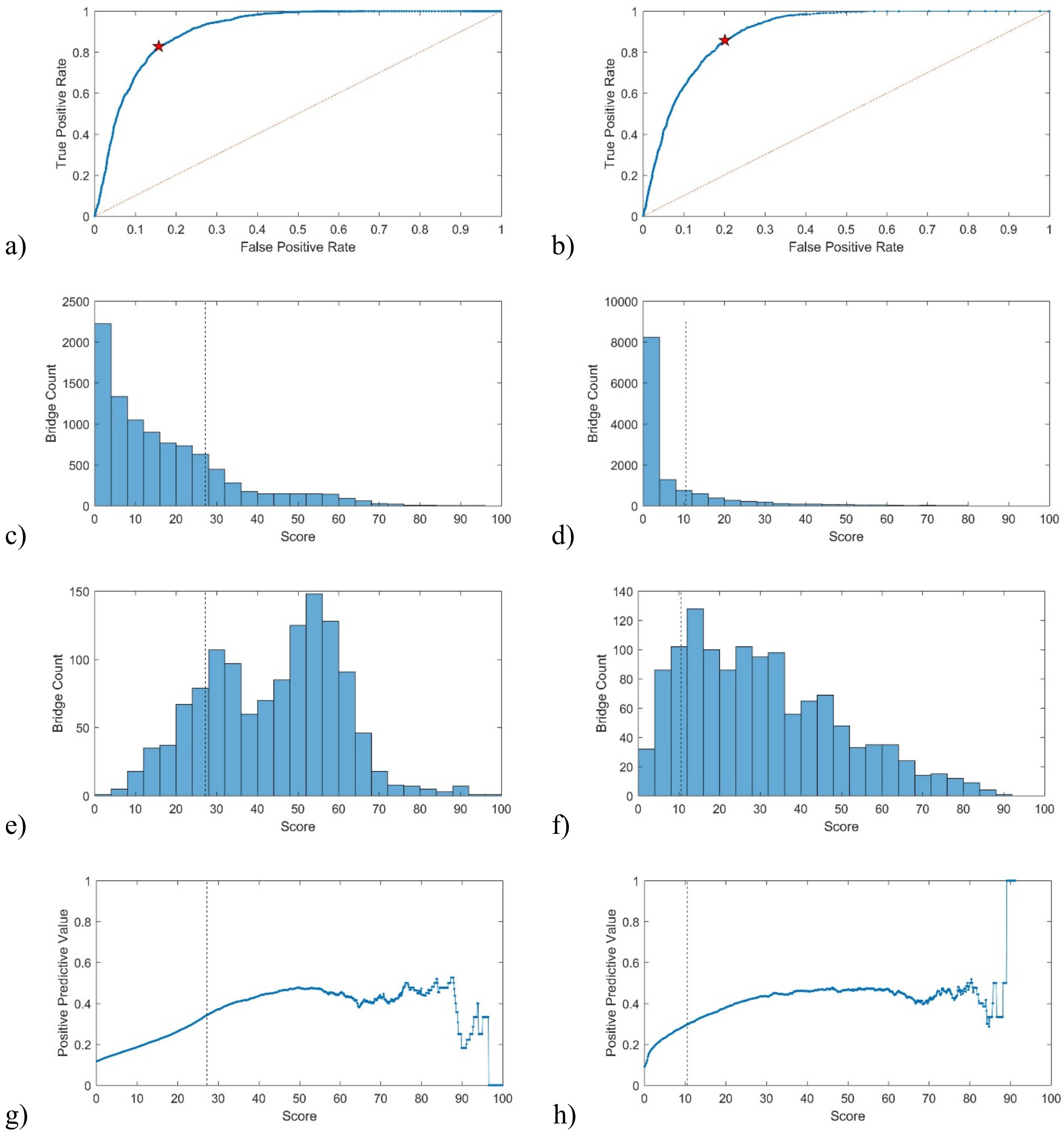


Figure 4.6. Comparison of ROC and distributions of scores for model developed from binary logistic regression with linear value functions and total maintenance costs: a) ROC curve for PRI; b) ROC curve for regression model; c) bridges not selected for replacement PRI scores; d) bridges not selected for replacement scores from regression model; e) bridges selected for replacement PRI scores; f) bridges selected for replacement scores from regression model; g) PV+ for PRI; h) PV+ for regression model

Table 4.5 presents the summary classification statistics for the regression models developed by optimizing an additive utility function using a genetic algorithm with linear constraints along with the classification statistics for the PRI for comparison. The additive utility function regression models were found to achieve AUC values and classification accuracies similar to those obtained using binary logistic regression. While these regression models develop the prioritization score using the same weighted average of value functions as used by the practitioner-derived models, the classification performance metrics were modestly improved by the regression, with all of the additive utility function regression models out-performing the models derived from the practitioner surveys for all of the statistical measures. These regression models were able to achieve the best sensitivity of any of the models, which indicates that these models identify a higher percentage of bridges scheduled for replacement using the threshold than any of the other types of model. As with the binary logistic regression models, the optimized additive utility function models all exhibited similar classification statistics regardless of the functional form of the value function or means of computing the maintenance costs.

Table 4.5: Classification Performance of Models Developed by Regression on Additive Utility Function

	PRI	ECDF Total Costs	ECDF Relative Costs	Linear Total Costs	Linear Relative Costs
AUC	0.906	0.895	0.894	0.897	0.895
Threshold	27.2	50.8	50.8	37.7	35.5
Sensitivity	82.8%	88.0%	85.3%	84.8%	86.5%
Specificity	84.2%	78.0%	79.7%	80.3%	78.7%
PV+	34.2%	28.4%	29.4%	29.9%	28.8%
PV-	98.0%	98.5%	98.2%	98.2%	98.3%
Accuracy	84.1%	78.9%	80.2%	80.7%	79.4%

Qualitative assessment of the computed distributions of scores reveals that the optimized additive utility function models developed using ECDF value functions were preferable to those developed using linear value functions. The additive utility function models developed using linear value functions were found to utilize only a narrow portion of the full range of the index, much like the models with linear value functions developed from the practitioner surveys. There was no notable difference in the distribution of scores for additive utility function models using ECDF value functions, so the model using maintenance costs computed relative to the estimated replacement cost was used since it resulted in slightly better classification metrics. Figure 4.7 presents the ROC curve, histograms of scores, and positive predictive value for this model alongside the same information for the current PRI for comparison. The histogram of scores provided by this model for bridges not selected for replacement are correctly skewed toward the low end of the scale with generally good separation from the optimized classification threshold. Likewise, the histogram for bridges selected for replacement produced by this model exhibits a nearly normal distribution of scores that is centered approximately 10 points higher than the optimized classification threshold. However, the range of scores assigned to bridges selected for replacement is fairly narrow compared to other indices and may present issues with distinguishing priority of individual replacement projects. The positive predictive values remain high over the range where these scores are concentrated, but do trend toward zero at the high end of the scale, which indicates that the bridge receiving the highest scores by this index are bridges that have not been selected for replacement.

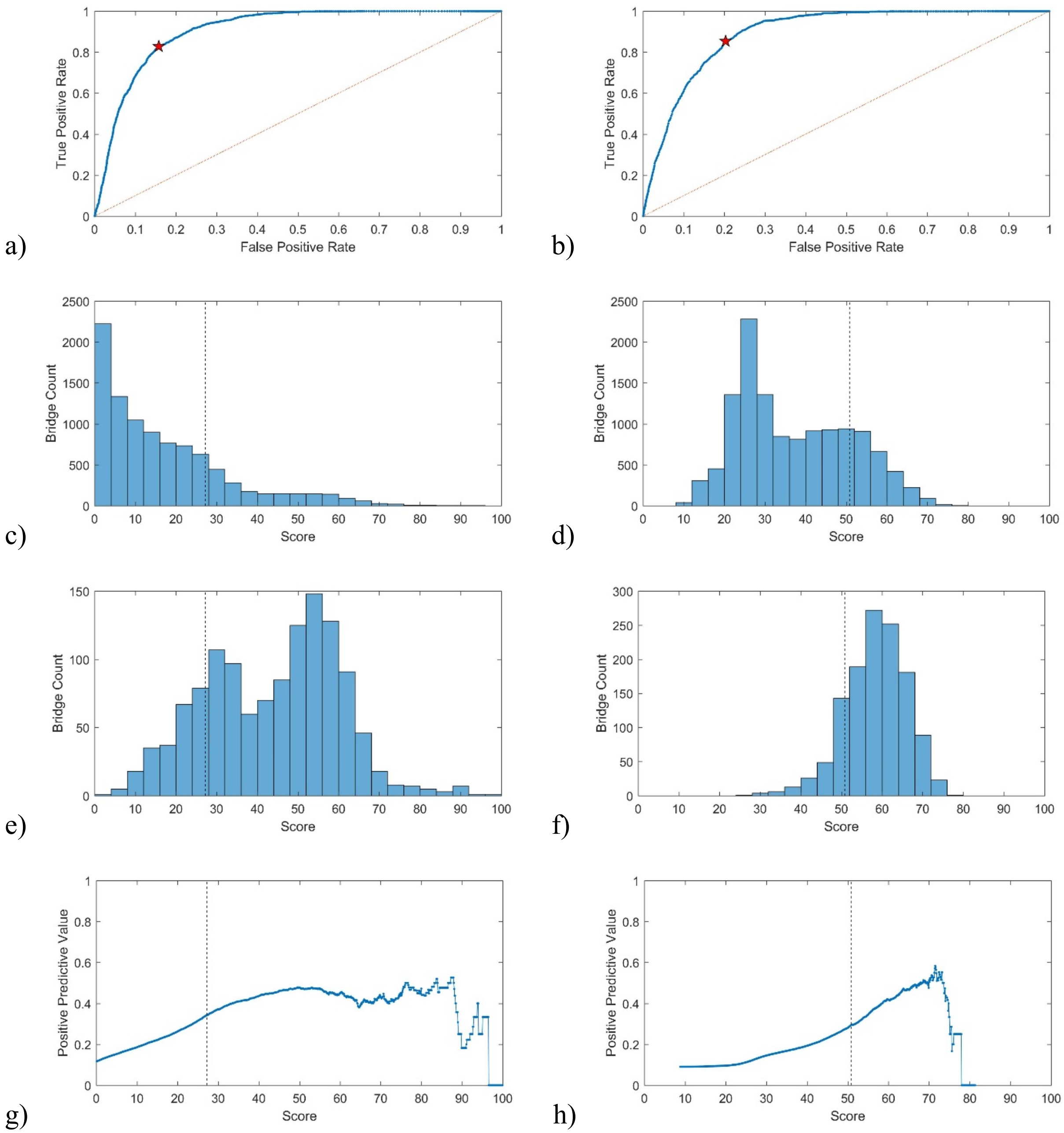


Figure 4.7. Comparison of ROC and distributions of scores for model developed from statistical regression of additive utility function with ECDF value functions and maintenance costs computed relative to the estimated replacement cost: a) ROC curve for PRI; b) ROC curve for regression model; c) bridges not selected for replacement PRI scores; d) bridges not selected for replacement scores from regression model; e) bridges selected for replacement PRI scores; f) bridges selected for replacement scores from regression model g) PV+ for PRI; h) PV+ for regression model

5. Recommendations

5.1 Recommendations for New Priority Replacement Index

The research yielded a large set of different prioritization models developed using practitioner surveys as well as two different statistical regression techniques. Across this set of models, different functional forms for the value functions that map individual performance measures to a normalized scale reflecting preference structure were explored. Value functions developed using the ECDF of the performance measures for all bridges in the North Carolina inventory were evaluated, since this method results in a uniform distribution of value scores and is consistent with the approached currently used by NCDOT within the Prioritization 5.0 framework under the STIP. In addition, linear value functions were evaluated, since linear functions are more readily implemented and have been suggested by the NCHRP 590 guidance. Furthermore, since this research proposed two new performance criteria incorporating current maintenance needs and historical maintenance burden within the prioritization, there was a need to evaluate whether these maintenance costs should be calculated using total maintenance costs or maintenance costs relative to the estimated replacement cost of the structure. As detailed in the prior section of this report, the performance of each model as a binary classifier of replacement status was assessed by applying establishing an optimized classification threshold and evaluating summary statistical measures for classification after applying each model to the bridge inventory in the North Carolina BMS. Additionally, the distributions of scores assigned to bridges not scheduled for replacement and bridges scheduled for replacement were assessed qualitatively to assess how well the models distinguished priority of individual bridges, avoided clustering of scores, and maximized the range of the index. Assessment of the distributions of scores was also aided through evaluating the positive predictive value of each model across the range of the index. Based on the classification performance metrics and distributions of scores, the following recommendations were developed:

1. As an important disclaimer to the scope of this research, it is emphasized that the prioritization formulae developed in this report are not intended to replace the decision-making process that involves direct coordination with Division Bridge Program Managers and Bridge Maintenance Engineers to select bridge replacement projects. There are many factors that influence the prioritization and selection of bridge replacement projects that cannot be effectively captured by the set of performance measures adopted in this research. Furthermore, the performance measures used are limited in their ability to describe the condition, history, and other site-specific factors associated with each bridge that are important to the decision-making process for bridge replacement. The indices developed and recommended for use can at best be used to provide a means for producing informed simulations within the BMS to forecast future needs and to assist in producing a list of potential bridge replacement projects to initiate the coordination with Division Bridge Program Managers and Bridge Maintenance Engineers.
2. The Priority Replacement Index was found to perform well in the binary classification of bridges currently selected for replacement in North Carolina. In fact, from a pure classification perspective, the PRI out-performed all of the developed models with better classification accuracy and positive predictive value at the optimized classification

threshold. However, the PRI has historically been used to preselect potential bridge replacement projects, so the correlation between this index and the classification of bridges selected for replacement is not entirely unexpected. While more effective at distinguishing the set of bridges currently selected for replacement from those not selected for replacement, the PRI still suffers from the problem of not providing a transparent link between performance criteria and measures and the priority score. As detailed in the review of the PRI, there are many instances of significant multiple counting of performance measures as well as nonlinear and case-specific formulas such that the relative impact of each performance measure on the PRI is unknown. In addition, the PRI does not consider maintenance needs or maintenance burden within the prioritization of replacement bridges and these considerations are known to influence the decision to prioritize the replacement of individual bridges. Lastly, although the PRI was revealed as the best binary classifier of current bridge replacement projects, the positive predictive value of the PRI was found to trend toward zero near the high end of the scale. This indicates that many of the bridges in the inventory that are currently receiving the highest PRI scores are not being selected for replacement.

If the PRI continues to be used as a metric for prioritization of bridge replacement projects, then the current threshold values of 30 and 50 that are used to delineate "good" and "very good" candidates for replacement have been deemed appropriate by the findings of this research. The optimal threshold value to simultaneously maximize sensitivity and specificity of binary classification with the PRI was found to be 27.2, which is very close to the threshold value of 30 used to indicate "good" candidates for replacement. Statistical analysis reveals that 34.2% of bridges receiving a PRI score greater than or equal to 27.2 are bridges that have been scheduled to be replaced. Analysis of the positive predictive value of the PRI as a function of the assigned score reveals that the positive predictive value reaches a maximum at a threshold score of 49.6, which is essentially the same as the current threshold used to indicate "very good" candidates for replacement. Approximately 48% of bridges receiving a PRI score greater than or equal to 49.6 are bridges that have been scheduled for be replaced.

3. Although the binary classification performance is slightly below that of the PRI, the prioritization model developed using binary logistic regression with linear value functions and maintenance costs computed relative to the estimated replacement cost was found to produce the best classification performance of the newly developed models and created distributions of prioritization scores that were improved relative to the PRI. This prioritization model can be implemented using the formula presented in Equation 3.4 with the regression coefficients defined in Table 5.1. The proposed model results in a favorable skew of scores for bridges not selected for replacement to the low end of the scale and distributes scores to structures scheduled to be replaced across a large range of the full scale of the index. Furthermore, the binary logistic regression models were the only ones to maintain high positive predictive value through the high end of the index, which means that the bridges receiving the highest scores by this model are bridges that actually are scheduled to be replaced, where in other indices, including the PRI, many of the bridges

receiving the highest scores are not bridges scheduled to be replaced. One of the primary benefits of this model is that the prioritization scale is actually a forecasted probability that the bridge will be selected for replacement. This provides a direct significance to the prioritization score and could facilitate the introduction of probabilistic techniques for network-level analysis in the BMS.

It is worth noting that best subset selection in the binary logistic regression eliminated a number of performance measures from the model that were found to not be statistically significant toward the classification of bridge replacement projects for this model. Before adopting this model, the Steering and Implementation Committee should review the omitted performance measures (deck condition, fracture criticality, underclearance rating, priority maintenance needs, recommended maintenance needs, and reoccurring burdensome maintenance costs) to decide if it is acceptable to utilize a prioritization formula that does not directly incorporate these measures.

Table 5.1: Regression coefficients for performance measures included in binary logistic regression model developed with linear value functions computed with total maintenance costs

Performance Measure	**Regression Coefficient**
Substructure Condition	0.06041
Superstructure Condition	0.03577
Scour Criticality	0.00828
Detour Length	-0.00621
ADT	-0.04260
Secondary	0.00366
Interstate	-0.00871
Bridge Posting	0.01093
Truck Traffic (ADTT)	0.01746
Deck Geometry Rating	0.02368
Burdensome	0.01920
Constant	-9.3170

4. If the NCDOT desires to implement the simplest, transparent model for prioritization of bridge replacement projects that incorporates the complete set of performance criteria and measures, then it is recommended that a simple weighted average of performance measures be used with relative weights established by the statistical regression performed with ECDF value functions developed with maintenance costs computed relative to the estimated replacement costs. This model out-performed the simple weighted average models developed from the practitioner surveys with respect to both classification accuracy and distribution of prioritization scores. The relative weights for the recommended simple weighted average model are presented in Table 5.2. It should be noted that several of the

relative weights for the performance criteria and measures differ significantly from those developed through the practitioner surveys. Specifically, the mobility performance criterion receives significantly higher weighting than indicated by the practitioner group's preference structure and the infrastructure condition criterion also receives moderately higher relative weighting. Likewise, the statistical model developed lower relative weighting for the maintenance needs, maintenance burden, and vulnerability criteria than indicated by the practitioner consensus. Prior to implementing the recommended simple weighted average priority replacement index, the Steering and Implementation Committee should review the identified optimal relative weights and assess whether they can reasonably reflect the decision making process used to prioritize bridge replacement projects.

Table 5.2: Recommended relative weighting of performance criteria and measures for implementation of a simple weighted average priority replacement index

Criteria or Measure	Relative Weights
Infrastructure Condition	**36.1**
Deck	1.2
Superstructure	6.5
Substructure	28.4
Vulnerability	**9.2**
Scour	5.0
Fracture Critical	4.2
Mobility	**30.5**
Detour Length	3.2
ADT	3.1
Primary	2.3
Secondary	3.6
Interstate	3.4
Bridge Posting	9.5
Truck Volume (ADTT)	5.4
Functionality	**8.4**
Deck Geometry Rating	5.8
Underclearance Appraisal	2.6
Maintenance Needs	**9.3**
Priority Needs	3.6
Recommended Needs	5.7
Maintenance Burden	**6.5**
Burdensome	3.1
Reoccurring	3.4

5.2 Extension of Metrics and Methodology to Replacement of Culverts

The performance criteria and measures proposed in this study for the prioritization of bridge replacement projects as well as the general methodologies employed could be extended to create similar practitioner-driven or data-driven models for prioritizing culvert replacement projects. During this study, the research team evaluated the availability of data in the AMS to compute performance measures for culverts in order to facilitate the development of a culvert priority replacement index. Figure 5.1 presents a potential tree of performance criteria and measures that could be used to develop such an index. In this figure, the performance criteria and measures used within the bridge prioritization that cannot be computed for culverts are highlighted in grey with a red “x” through them. For each of these measures, the underlying data is either not collected and recorded in the BMS for culverts or in some cases, like scour vulnerability, all culverts were found to receive the same rating within the BMS and so inclusion of these measures would serve no benefit to the priority replacement index. However, all of the performance measures under the mobility performance criterion can be computed for culverts and, importantly, the research team has confirmed that both maintenance history and inspector recommended maintenance needs are available for culverts so these performance criteria can also be used for prioritizing culvert replacement projects. Furthermore, the research team identified three additional performance measures that are suggested for use in the prioritization of culvert replacement projects: Culvert Condition Rating (to be used as the sole performance measure for the Infrastructure Condition criterion) and Channel Rating and Waterway Adequacy (to be used as performance measures for the Functionality criterion).

During the course of the effort, the research team was unable to acquire a list of active or scheduled culvert replacement projects in order to facilitate statistical regression of relative weights for each of the proposed performance measures in order to develop a culvert priority replacement index. Performance Master databases from the BMS were exported and queried to explore the potential of using past culvert replacement projects as an alternative to active and scheduled projects to facilitate the statistical modeling. However, in contrast to bridges, very few culvert replacement projects have occurred on an annual basis according to the analysis of the Performance Master databases. Specifically, analysis of the 2012 Performance Master data relative to the 2017 Performance Master data revealed that only 25 culvert records reflected a replacement over the entire five year period. This sparsity of culvert replacements would not provide an adequately large sample size for the research team to employ the statistical techniques, such as binary logistic regression or constrained linear regression, to quantify the relative importance of the various performance measures to the selection of culvert replacement projects. Consequently, any development of a prioritization index for culverts would likely need to rely on practitioner surveying unless NCDOT has a larger list of active and scheduled culvert replacement projects suitable for application of statistical regression techniques.

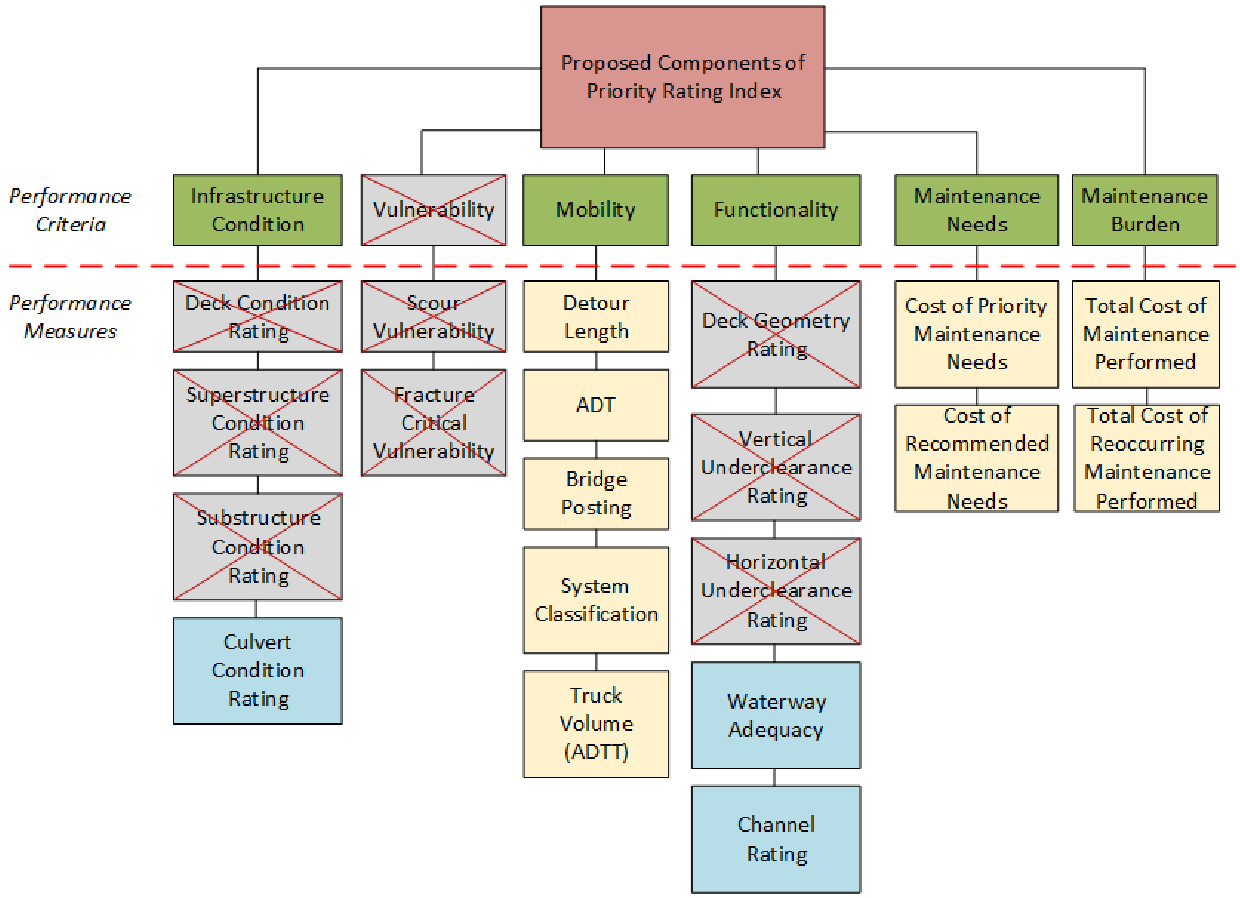


Figure 5.1. Potential tree of performance criteria and measures for culvert replacement projects using data readily accessible within the AMS

6. Implementation and Technology Transfer Plan

The Steering and Implementation Committee is encouraged to review the findings of this research effort and evaluate the recommendations enumerated in the previous section of this report. Based on the recommendation adopted by the Steering and Implementation Committee, the following details on implementation are provided:

1. If the PRI is retained as an index for prioritization of bridge replacement projects, then little is needed to be done to implement the research results. As indicated in the analysis, the current threshold values of 30 and 50 used to distinguish “good” and “very good” candidates by the PRI have been supported as optimal by the statistical analysis performed.
2. If NCDOT choses to adopt the binary logistic regression model capable for predicting the probability that a bridge will be replaced based on the performance measures, then this could be implemented within the BMS fairly readily since linear value functions are easily implemented and the formula for computing the probability with a binary logistic regression model is a simple equation. The most challenging obstacle toward implementation would be to facilitate the linkage between the MMS and BMS to compute the maintenance burden performance measures used in the binary logistic regression model.
3. If NCDOT choses to implement a new prioritization formula that is based on an additive utility function (i.e. a simple weighted average of performance measures), then this could also be readily implemented in the BMS since it is simply a weighted average of value functions computed on the performance measures. This implementation would also require development of a linkage between the MMS and the BMS to compute the maintenance burden performance measures, or periodic calculation of this performance measure outside of the BMS followed by importing to the Network Master the values computed for each bridge for these performance measures. The recommended model does utilize ECDF value functions, so empirical cumulative distribution functions would need to be computed for each performance measure either within or external to the BMS. NCDOT computes ECDF value functions for performance measures used to prioritize other transportation projects, so the tools and expertise needed for this step of the implementation process likely already exist at NCDOT.
4. As an alternative to choosing a single index, all three indices could be applied to the potential bridge replacement projects in the BMS. Consensus amongst the three indices could be used to further distinguish replacement projects with highest priority for replacement or eliminate consideration of projects with consistently low priority across all three indices. Likewise, projects receiving high prioritization scores by only one of the three indices may receive greater scrutiny as a potential outlier during manual review and selection of bridge replacements than projects receiving high prioritization scores from multiple indices.

The research team is committed to any implementation model selected by the Steering and Implementation Committee and will assist with any necessary technology transfer. The research team has retained all databases and scripts used to develop the value functions for the individual performance measures, perform the statistical regressions, and assess the classification performance and distributions of scores developed by the individual models. Additionally, the practitioner survey tools and spreadsheets and scripts used to post-process the survey responses to arrive at relative weights based on either Direct Weighting or Analytic Hierarchy Process have been retained. In the event that NCDOT is interested in extending the practitioner surveys to culvert replacement projects, these tools can be transferred to the department for this use.

7. Cited References

Adams, P., Aktan, A. E., Dubbs, N., DePriest, M., Minaie, E., Moon, F.L., and Ozalis S. (2014). NJDOT Risk-Based Prioritization of Structurally Deficient Bridges. Rutgers University. New Jersey Department of Transportation.

Alar, A. (2018) "Development of Bridge Management Tools for Predicting Bridge Replacement Projects," Masters of Science Thesis, Department of Civil and Environmental Engineering, University of North Carolina at Charlotte, 140 p.

Amekudzi, A. and Meyer, M. (2011). Best Practices in Selecting Performance Measures and Standards for Effective Asset Management. Report FHWA-GA-11-0903. /Georgia Department of Transportation. Forest Park, GA.

Colorado Department of Transportation (2017). Transportation Planning in Colorado. CDOT Planning Manual. Denver Colorado. Available at: https://www.codot.gov/programs/planning/documents/planning-partners/planning-manual.

Farrar, M. M. and Newton, B. (2014). "Perspective: The AASHTO Manual for Bridge Element Inspection." ASPIRE. Winter 2014.

Fawcett, T. (2006) "An introduction to ROC analysis." Pattern Recognition Letters, Vol. 27, p. 861-874.

Federal Highway Administration. (1995). Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. U.S. Department of Transportation Federal Highway Administration. Office of Engineering Bridge Division.

Federal Highway Administration. (2012). Moving Ahead for Progress in the 21st Century (MAP-21). Available at: https://www.fhwa.dot.gov/map21/

Florida Department of Transportation. (2012). Prioritizing Florida's Highway Investments 2012-2013. Florida Department of Transportation, Tallahassee, Florida.

Garrett, P. (2012). Priority Replacement Index Definition. Email message to Whelan, M., and Cavalline, T. August 2015.

Hosmer, D.W., Lemeshow, S., and Sturdivant, R.X. *Applied Logistic Regression*, Vol. 398, John Wiley & Sons, 2013.

Johnson, M. and Ozbek, M. (2013). "Developing Bridge Management Components that Facilitate Decision-Making." Transportation Research Record: Journal of the Transportation Research Board, No. 2360, Transportation Research Board of the National Academies, Washington, DC, 1-810.3141/2360-09.

Keeney, R.L., and Raiffa, H. (1993). Decisions with Multiple Objectives – Preferences and Value Tradeoffs (reprint). Cambridge University Press. New York, New York.

Lane, K.M. (2016). Performance criteria and measures for prioritization of bridge replacement projects. MS Thesis. University of North Carolina at Charlotte. Charlotte, North Carolina.

Michigan Department of Transportation (2016). 2016 System Performance Measures Report. Michigan Department of Transportation. Lansing, Michigan. Available at: https://www.michigan.gov/documents/mdot/MDOT-Performance_Measures_Report_289930_7.pdf. Accessed May 2019.

New York State DOT (2014). New York State DOT Transportation Asset Management Plan. Available at: https://www.tamptemplate.org/wp-content/uploads/tamps/023_newyorkstatedot.pdf. Accessed May 2019.

North Carolina Department of Transportation. (2018). Prioritization 5.0. Master Presentation. North Carolina Department of Transportation. Raleigh, NC. Available at: https://connect.ncdot.gov/projects/planning/MPORPODocuments/P5.0%20Master%20Presentation%20-%20July%202018.pdf. Accessed May 2019.

Ohio Department of Transportation. (2003). Local Major Bridge Program Standard Procedure. Title 23, U.S.C., CFR-650. Standard Procedure No. 310-004(SP). Ohio Department of Transportation. Columbus, Ohio.

Oklahoma Department of Transportation. (2015). Moving Oklahoma Forward. Long Range Transportation Plan. Oklahoma City, OK.

Oregon Department of Transportation. (2015.) 2015 Bridge Condition Report. Bridge Section. Oregon Department of Transportation. Salem, Oregon.

Patidar, V., Labi, S., Sinha, K., and Thompson, P. (2007). NCHRP Report 590: Multi-Objective Optimization for Bridge Management Systems. Transportation Research Board. Washington, DC.

Saaty, R.W. (1987) "The Analytic Hierarchy Process – what it is and how it is used," Mathematical Modelling, Vol. 9, No. 3-5, p. 161-176.

Selin, T. (2015). Performance-Based Planning Weighting Performance Measures as a Method to Refine Project Evaluation. Cambridge Systematics, Inc.

Shepard, R.W. and Johnson, M.B. (2001). "California Bridge Health Index: A Diagnostic Tool to Maximize Bridge Longevity, Investment." TR News. No. 215. Transportation Research Board. July-August 2001.

Sobanjo, J. O. and Thompson, P. D. (2016). Implementation of the 2013 AASHTO Manual for Bridge Element Inspection. Florida Department of Transportation. Tallahassee, Florida.

South Carolina Department of Transportation. (2013). Act 114 Prioritization Requirements. Office of Secretary of Transportation.

South Dakota Department of Transportation (2016). Bridge Improvement Grant (BIG) Procedure. Office of Local Government Assistance. Available at www.scdot.com

Szary, P. and Roda, A.M. (2014). Bridge Resource Program. Center for Advanced Infrastructure and Transportation. New Jersey Department of Transportation. Final Report. 435056-9.

Tennessee Department of Transportation (2018). "High Priority Bridge Replacement Program (HPBRP). Available at:

https://www.tn.gov/content/dam/tn/tdot/programdevelopment/localprograms/funding-options/High_Priority_Bridge_Replacement_Program.pdf

Vermont Agency of Transportation. (2015). Background Information Emphasis Areas and Project Prioritization. State of Vermont. Agency of Transportation. Montpelier, Vermont.

Utah Department of Transportation (2014) Bridge Management Manual. Chapter 2, Planning and Programming. Salt Lake City, Utah. Available at: https://udot.utah.gov/main/uconowner.gf?n=12590300900442134

U.S. Department of Transportation (2012). *Moving Ahead for Progress in the 21st Century Act (MAP-21)*. Federal Highway Administration. https://www.fmcsa.dot.gov/mission/policy/map-21-moving-ahead-progress-21st-century-act. Accessed 22 June 2016.

8. Appendix A: Literature Review

A.1 Introduction

State highway agencies (SHA) are tasked with maintaining, repairing, and replacing bridges to support the travelling public. Faced with an aging infrastructure, increasing traffic, and less than optimal financial conditions, agencies must develop programs that prioritize candidate projects in a manner ensuring that bridges are selected for maintenance, repair, and replacement (MR&R) at appropriate times and within budget constraints. To accomplish this, prioritization methods must be developed that utilize and appropriately weigh the desired performance measures and agency preferences to identify candidate bridges that, if selected, help a state agency achieve prioritization criteria.

North Carolina Department of Transportation (NCDOT) is responsible for maintaining the second largest state-maintained road network in the United States (US) with highway assets value of $575 billion (NCDOT, 2016). These assets consist of pavements, bridges, and culverts among other transportation structures. There are approximately 13,500 bridges in North Carolina with an estimated asset value of $60 billion. The Bridge Maintenance Improvement Plan (BMIP), the funding program for bridge replacement and rehabilitation projects has a funding need of $250 million per year (NCDOT, 2016). The NCDOT goal for 2030 is to reduce the number of structurally deficient (SD) bridges, or bridges that are in relatively poor condition," to 10% or less.

A.2 Overview of Bridge Management Systems and Project Prioritization

In response to the collapse of the Silver Bridge over the Ohio River, National Bridge Inspection Standards (NBIS) were developed in the 1970's. These standards required that all state-maintained bridges be placed in an inventory and inspected every two years for condition. From these inspections, changes in the physical condition of the bridge are measured to determine the actions required to ensure satisfactory condition and safety to the public. Each year, the FHWA acquires bridge data for the National Bridge Inventory (NBI) database. From this information, the state of the National Network of Highway Bridges can be assessed and tracked over time. As of 2017, of the 614,387 bridges in the United States, 56, or 9.1%, are considered structurally deficient (ASCE, 2017). Each state highway agency (SHA) or Department of Transportation (DOT) spends millions of dollars each year repairing, replacing, and maintaining existing infrastructure (AASHTO, 2008; ASCE 2016). At both the federal and state level, various means and tools are utilized to manage the vast amount of data associated with existing and pending projects.

Most SHA have specific management plans for collection, storage, and use of data to support transportation infrastructure monitoring, maintenance, rehabilitation, and replacement. Many states use a Bridge Management System (BMS) to organize NBI and supporting data and to aid in prioritizing bridges for maintenance, repair and replacement (MR&R). The data found in these systems often includes items such as location, road type, structure type, detour lengths, and other design, geographic, and performance data (Son and Sinha, 1997). Not only can a BMS act as a storage system, but it can also can be used to help organize the information to help predict bridge deterioration rates and associated costs for maintenance, repair, rehabilitation, and replacement (Sinha et al., 2009). Researchers have found that having an up-to-date, robust BMS not only assists in ensuring appropriate MR&R activities are performed, but also increases their service life (Hearn et al., 2013). Currently, there are a number of BMS used throughout the world. AASHTO Bridge Management software (BrM) is the most widely used in the U.S.

In 1987, research led by Dr. David Johnston at North Carolina State University (NCSU) helped NCDOT create one of the first BMS in the United States (Chen and Johnston, 1987). Since this time, the NCDOT BMS has expanded to include records for the over 17,000 in-service bridges, along with over 200 items of operational and functional information, including bridge condition from the past inspection. Currently, NCDOT utilizes a software platform developed by AgileAssets to support its BMS. Over the past several years, NCDOT has invested resources into updating and enhancing the BMS, including the development of updated deterioration models and user costs (Chen and Johnson, 1987; Abed-Al-Rahim and Johnson, 1991; Duncan and Johnson, 2002; Cavalline et al., 2015). Additional enhancement to support project prioritization and identification of multiple feasible MR&R options to achieve a desired level of service is still needed, and work presented within this report is part of this effort.

Prioritization methods provide a framework for SHA to select bridges for MR&R and replacement. Means of identifying, organizing, and weighting criteria important to an agency can utilize concepts from conventional decision analysis. Decision analysis is the process of arranging criteria in order of preference to select the best candidate. Sometimes, decision analysis can be easily performed, for example when the preferred order is based purely on cost. Other times, the situation is more complex and multiple factors (such as cost, safety, impact to the traveling public, and risk) affect the ranking. Conflicting criteria can also be an issue. Decision makers are often faced with the process of value trade-off, which is when a choice must be made between the benefits derived from one criterion relative to another (Patidar et al., 2007).

To develop prioritization strategies, sets of performance criteria deemed important to the stakeholders and performance measures designed to quantify the significance or opportunities offered by specific decisions or projects to these performance criteria must be identified. Performance criteria, which are referred to (somewhat interchangeably) as "goals" or "criteria" throughout literature, define the alternative actions and trade-offs within a decision. Performance measures are used to assess progress towards meeting the performance criteria. A performance measure is the quantitative or qualitative impact of a specific physical action or policy that reflects a concern of the policy maker, user, or community (Patidar et al. 2007). Performance measures should satisfy the following criteria (Keeny and Raiffa 1976):

- completeness, covering all of the important parts of the problem
- operativeness, being readily calculated from available data
- non-redundancy, avoiding double counting, and
- minimalness, keeping the size of the problem dimensions as small as possible.

Measures of the relative importance of project attributes and impacts should also be considered, along with the risk attitudes of the stakeholders. Additionally, the ranking or scoring system used in the prioritization methodology should suitably scale the results to allow a clear identification of candidate bridges through an appropriate spread in ranking. Ultimately, a prioritization index should provide a SHA with the ability to understand the implication of specific factors in the rankings and produce suitable resolution to facilitate consideration of multiple alternatives for implementation.

A.3 Bridge Project Prioritization in North Carolina and Recent Legislation

A.3.1 Historical Bridge NCDOT Project Prioritization

Over the years, the North Carolina Department of Transportation (NCDOT) has utilized various methods to guide bridge project prioritization and selection. The method used prior to 1990 was simply preparation of a list of possible bridge candidates, developed by NCDOT personnel, which was distributed among division bridge supervisors (Garrett, 2012). The list included all candidate bridges and the appropriate ratings. As an initial screening process, each of the bridges on the list had to meet specific eligibility requirements for federal funds:

- Sufficiency Rating < 50
- Structurally Deficient or Functionally Obsolete
- Minimum 20' span along roadway

The supervisors of the bridge project prioritization process would then compile a list detailing the reasons each bridge project candidate met the requirements. The final list was then reviewed and the candidates were programmed (Garrett, 2012).

In the early 1990's, Dr. David Johnston at NCSU developed both a new software program to assist with NCDOT's bridge management needs and a new rating formula called Deficiency Points. Deficiency Points is a collection of performance measures developed through prior NCDOT-sponsored research that represent the level of inadequacy of a bridge in terms of expected functionality and is computed on a 100 point scale (Johnston and Zia, 1984). The software program, called OPBRIDGE, was supported by the NCDOT mainframe computing system. Algorithms within the program facilitated computation of bridge performance metrics such as Deficiency Points, and compared bridge performance ratings against one another to help with the selection process. OPBRIDGE was capable of providing a list of all non-scheduled bridges, and provided Deficiency Points, Sufficiency Ratings, forecasted deck conditions, and other important information useful in selecting and prioritizing bridge projects.

Each division of the state produced a list of the "Top 20" candidate bridge projects to be compared with the top candidate bridge projects from other divisions. To optimize the list, each candidate project was entered into the system twice. The first run was based solely on the priorities provided by the division, the second considered only all non-scheduled bridge projects. A final list was then sorted by Deficiency Points and sent to a committee for review and selection of the MR&R projects. If additional funds were available, the OPBRIDGE optimization program was utilized to help identify additional candidate bridge projects. The final list would then be reviewed and programmed into the Transportation Improvement Program (TIP) (Garrett, 2012).

A.3.2 Recent Legislative Requirements

In 2012, the Federal Highway Administration (FHWA) established MAP-21 legislation that provides a new framework for US transportation policy and funding allocation (FHWA, 2012). Although MAP-21 provides flexibility for states to identify and select candidate projects, it does mandate performance measurement and transparency in the allocation of funding to ensure accountability to the public. One of the primary performance-based planning aspects of MAP-21 is a set of seven thematic performance criteria areas: safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays. States are tasked with developing measures and targets towards these seven performance criteria that can be utilized to demonstrate progress concerning transportation improvements that address the national goals.

Although compliant with MAP-21, a wide variety of strategies for SHA funding allocation exist at the current time. For example, in Idaho, a total of 20% of funding is for work on state-owned structures is for preservation and 80% is for restoration (Hearn et al. 2013). Michigan requires 22% of funding for bridges to go to preventative maintenance and 78% to rehabilitation and replacement (Hearn et al. 2013). Virginia uses 28% of funding for prevention, restoration and rehabilitation, the remaining 72% is used for structural replacement (Hearn et al. 2013).

In 2013, the General Assembly of North Carolina enacted House Bill 817, the Strategic Transportation Investments Law (also known as the STI) (NCDOT, 2013). In the spirit of MAP-21, the STI mandates that all transportation projects funded through either the State Highway Trust Fund or Federal Aid programs be prioritized and selected using quantitative measures, and as appropriate, qualitative measures and local input. Specific allocations of funds to Statewide Strategic Mobility Projects, Regional Impact Projects, and Division Needs Projects are prescribed in the STI, along with specific weights of measures for quantitative performance criteria. Although bridge replacement projects and interstate maintenance projects are exempt from this legislation, NCDOT has expressed the need to implement the same approach of objective and transparent prioritization for effective optimization of bridge project decisions, as well as justification of projects included in these work programs.

Funding is divided into three tiers of projects: 1) Statewide Strategic Mobility, which includes interstates, tolls, National Highway System routes, and STRAHNET routes; 2) Regional Impact, that includes US and NC highway routes; and 3) Division Needs, which includes other state highways and municipal routes, as shown in Figure A.1.

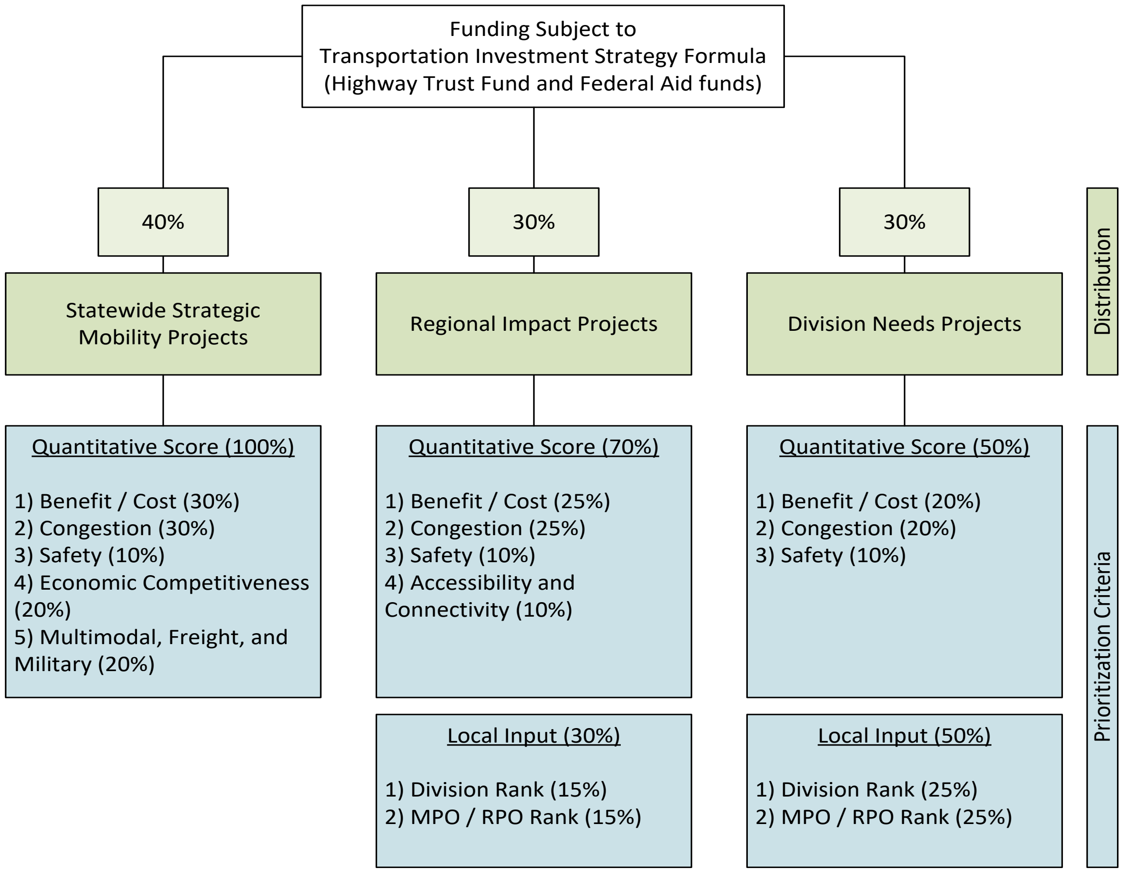


Figure A.1: Overview of Strategic Transportation Investment prioritization funding plan with 2013 criteria proposed by Board of Transportation for Highway projects

Under each category, the project selections are based on an objective rating on a scale of 0-100. Potential projects are scored using quantitative data and, sometimes, additional qualitative data and local inputs. The performance criteria can vary based on the type of project, but generally include; benefit cost analysis, safety, impact on economic competitiveness, alleviation of congestion, and multimodal benefits. The ratified STI law stipulates that bridge replacement, interstate maintenance, and highway safety improvement projects are all subject to the same investment formula as other transportation projects in the state.

NCDOT utilizes the project prioritization schemes outlined in Prioritization 5.0 (or P5.0) to allocate funds for transportation projects subject to the STI (NCDOT, 2018). Designed to meet the requirements of North Carolina's STI legislation, P5.0 was developed by a Prioritization Workgroup of metropolitan planning organizations (MPOs), rural transportation planning organizations (RPOs), division engineers, and local government advocacy groups. The STI legislation provides a funding formula for all capital expenditures, which draw from the NC Highway Trust Fund, and is designed to fund the "best" transportation projects regardless of mode. P5.0 provides a framework for funding allocation for highway, non-highway, aviation, bicycle/pedestrian, ferry, and rail mobility projects.

The P5.0 Highway Criteria incorporates ten performance criteria, each defined with one or more performance measures (Table A.1). Each performance criterion is weighted based on the funding category, which uses both quantitative data, performance measures, and local input. The performance criteria are aspects related to highway infrastructure based not only on condition, but how it impacts the community in which it is located. Division and local input, as well as MPO/RPO input are also included in the total score, as shown in Table A.2.

Table 2.1: NCDOT P5.0 highway performance measure weighting (NCDOT, 2018)

Performance Criteria	Performance Criteria Weight	Performance Measure	Measure Weight
Congestion	30%	Existing Volume / Capacity Ratio	60% (Statewide)
			80% (Regional)
			100% (Division)
		Existing Volume	40% (Statewide)
			20% (Regional)
			0% (Division)
Benefit-Cost	25%	Benefit-Cost	25%
Freight	25%	Truck Volume	50%
		Volume / Capacity	30%
		Distance to Freight Terminal	20%
Safety	10%	Crash Density	20%
		Crash Severity	20%
		Critical Crash Rate	20%
		Safety Benefits	40%
Economic Competitiveness	10%	% Change in County Economy	50%
		Change in Jobs	50%

Table 2.2: NCDOT P5.0 Highway criteria and weights (NCDOT, 2018)

Funding Category	Quantitative Data	Local Input	
		Division Rank	**MPO/RPO Rank**
Statewide Mobility	Congestion = 30% Benefit-Cost = 25% Freight = 25% Safety = 10% Economic Competitiveness = 15%	--	--
	Total = 100%		
Regional Impact	Congestion = 20% Benefit-Cost = 20% Safety = 10% Accessibility / Connectivity = 10% Freight = 10%	15%	15%
	Total = 70%		
Division Needs	Congestion = 15% Benefit-Cost = 15% Safety = 10% Accessibility / Connectivity = 5% Freight = 5%	25%	25%

	Total = 50%		

Depending on the funding category, each performance criteria is incorporated into the prioritization formula and the appropriate weights for each criterion is applied. For example, the Division Needs weighting would be computed using the following steps, with the weightings as shown in Table A.1 and Table A.2:

Division Needs = 0.25 (Division Rank) + 0.25 (MPO / RPO Rank) + 0.50 (Quantitative Data) (A.1)

where:

Quantitative Data = 0.15 (Congestion) + 0.15 (Benefit-Cost) + 0.10 (Safety) + 0.05 (Accessibility / Connectivity) + 0.05 (Freight) (A.2)

Congestion = 0.60 (Existing Volume / Capacity Ratio) + 0.40 (Existing Volume) (A.3)

Benefit-Cost = 1.00 ((Travel Time Savings $ + Safety Benefit $)/Cost) (A.4)

Safety = 0.33 (Crash Density) + 0.33 (Crash Severity) + 0.33 (Critical Crash Rate) + 0.50 (Crash Frequency) + 0.50 (Severity Index) (A.5)

Region A and Divisions 1, 5, 6, 7, 8, 11, and 13 utilize area-specific criteria weights for regional impact and division needs scoring, including weight additions and reductions for area-specific priorities such as those listed previously or additional priorities such as pavement condition (NCDOT, 2018). These are shown in Table A.3.

Table A.3. NCDOT P5.0 Area-specific criteria weights

Location	Weight Reductions	Weight Additions
Region A	-5% Congestion	+5% Freight
Division 1	-5% Freight -10% Benefit/Cost -10% Congestion	+10% Safety +15% Accessibility/Connectivity
Division 5	-5% Freight -5% Accessibility/Connectivity	+5% Benefit/Cost +5% Safety
Divisions 6, 7, 8, 11	-5% Freight	+5% Safety
Division 13	-5% Accessibility/Connectivity	+5% Safety
Division 14	-5% Freight -5% Accessibility/Connectivity	+10% Pavement Condition

Although these performance criteria share some overlap in both scope and intent with the federal performance criteria included in the MAP-21 legislation, the identification of specific quantitative measures, setting of performance targets, and development of useful prioritization indices has not yet been performed for bridges. Guidance on methodologies to develop network- and project-level prioritization routines for bridge management systems (BMS) was synthesized as part of a study funded by the National Cooperative Highway Research Program (NCHRP), with findings summarized in NCHRP Report 590, Multi-Objective Optimization for Bridge Management Systems (Patidar et al. 2007). This report provides guidance to agencies interested in developing network-level and bridge-level optimization models.

A.3.3 Priority Replacement Index (PRI)

Beginning in 2012, two key changes were made to NCDOT's bridge project prioritization process. First, NCDOT would no longer have access to OPBRIDGE due to changes in the agency's computer network. Second, the Priority Replacement Index (PRI) was developed for use in lieu of Deficiency Points. The PRI is a fairly robust and intricate index, utilizing both Deficiency Points and Sufficiency Rating in the computation, along with the structural & functionality assessment and temporary shoring needs, to compute the index. The decision to develop and utilize the PRI was based on the opinion of NCDOT personnel that Deficiency Points did not have an efficient linear scale. The performance measures that are used for calculating the PRI are nationally utilized metrics that are indexed in the National Bridge Inventory (NBI) (FHWA, 1995). The current PRI is computed on a 120 point scale, where the higher the number of points a bridge is assigned on the scale, the more likely that the given bridge is a good candidate for replacement. The PRI equation is:

$$\text{PRI} = 0.45(\text{Deficiency Points}) + 0.45(100 - \text{Sufficiency Rating}) + 1.25[28 - \text{Deck Condition} - \text{Superstructure Condition} - 2(\text{Substructure Condition})] + 10(\text{Temporary Shoring}) \quad \text{(A.6)}$$

Ideally, the PRI ranking was intended to serve as an objective and actionable method for clearly distinguishing bridges requiring replacement rather than repair or rehabilitation and sorting the projects in order of priority. While there are no fixed thresholds used to identify replacement candidates, a general guideline has been suggested to separate the PRI scale into three ranges for replacement. Under this guideline, bridges with a PRI score from zero up to 30 are considered "poor candidates" for replacements, bridges with a score of 30 up to 50 are considered "good" candidates, and bridges with a score of 50 or higher are considered "very good" candidates for replacement.

As described in section A.3.1, the Deficiency Points index was designed to quantify the likelihood and urgency for a bridge replacement with higher point totals being associated with greater priority. Four main performance criteria are addressed in the Deficiency Points calculation: single vehicle load capacity, vertical roadway under/over clearances, estimated remaining life, and clear deck width. The performance criteria in the Deficiency Points calculation focus heavily on vehicle to bridge posting weight ratios, functionality appraisal ratings, geometry, Average Daily Traffic (ADT), and estimated remaining life.

The Sufficiency Rating is a federal rating that was previously used to determine eligibility for federal funding to repair or replace each bridge (FHWA, 1995). It is an overall rating of structural adequacy, functionality, and essentiality of use and is computed on a 100 point scale. Since this rating evaluates sufficiency rather than deficiency, bridges with lower Sufficiency Ratings are often considered to be more suitable candidates for replacement. The Sufficiency Rating is based upon four performance criteria: structural adequacy and safety, serviceability and functional obsolescence, essentiality for public use, and special reductions. The performance criteria are calculated through a number of both linear and nonlinear equations that utilize 19 different performance measures sourced from the NBI data. Further information on the Sufficiency Rating can be found in the NBI Recording and Coding Guide (FHWA, 1995).

The remaining components of the PRI are general condition ratings (deck, superstructure, and substructure) and an additional binary assignment of points that are incorporated if the structure has been provided with temporary shoring. The condition ratings are overall ratings of the three principal components of the bridge assigned by a bridge inspector using a 0 to 9 scale. Along with the additional points assigned to bridges with temporary shoring, the additional points provided to the PRI by these condition ratings are designed to provide greater priority for replacement to structures in an advanced state of deterioration with potentially significant reductions in load carrying capacity.

Currently, NCDOT bridge engineers believe that the PRI does a poor job of indicating which bridges should be replaced based on anecdotal evidence obtained through current and prior practice. To compute each component of the PRI, a number of performance measures are utilized with sometimes complex, non-linear functions used to assign scores. Performance measures in the PRI encompass a broad range of bridge characteristics, and the impact of some of these characteristics on the PRI scoring is not readily evident based on the complexity of the scoring. Double-counting (or multiple-counting) exists, as well as underrepresented factors of interest to NCDOT and over-represented metrics that skew the index.

Early in this study, an analysis was performed to investigate if the PRI is in fact a poor indicator for bridge replacement projects by evaluating the PRI scores of bridges that have been selected for replacement relative to the remaining bridges in the state inventory that are not scheduled to be replaced. This was based on bridge data sourced from the 2016 Network Master database along with a list of all bridges either currently being replaced or scheduled for replacement that was provided by the NCDOT. This analysis consisted of records for 13,826 bridges of which 1,249 or 9.03% were currently scheduled for replacement. The distributions of PRI scores among bridges selected for replacement and those not selected for replacement were used to evaluate the performance of the PRI as a means of classifying bridge replacement projects and to postulate reasons for shortcomings in the performance of the index.

The histograms of PRI scores for bridges that are selected for replacement and those not currently selected for replacement are shown in Figure A.2 and Figure A.3, respectively. On average, bridges selected for replacement do tend to have higher PRI scores than those not selected for replacement, however a closer examination of the data reveals issues within the index. First, the histograms reveal that bridges selected for replacement exhibit a bimodal distribution of scores that has mean and median values in the lower half of the index range and a spread that encompasses a large portion of the index range. Ideally, a prioritization index should clearly distinguish replacement projects from all other bridges with a distribution that is skewed toward the higher end of the index range, but with a good spread that does not cluster the scores so that there is a clear indication of priority between different projects. To illustrate, the red lines in Figures A.2 and A.3 represent ideal distributions for both classification and priority ranking of bridge replacement projects.

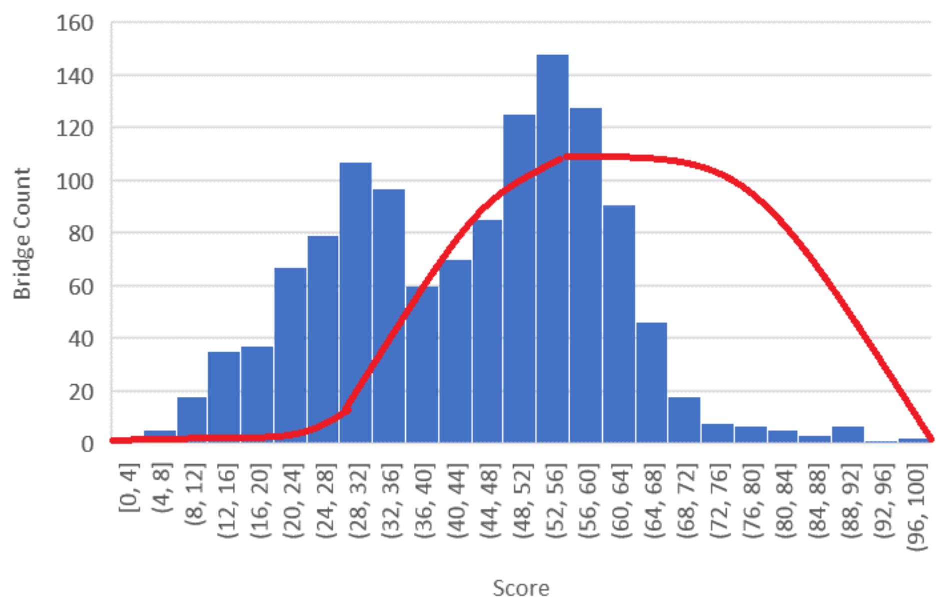


Figure A.2: Histogram of PRI Scores for Bridges Selected for Replacement

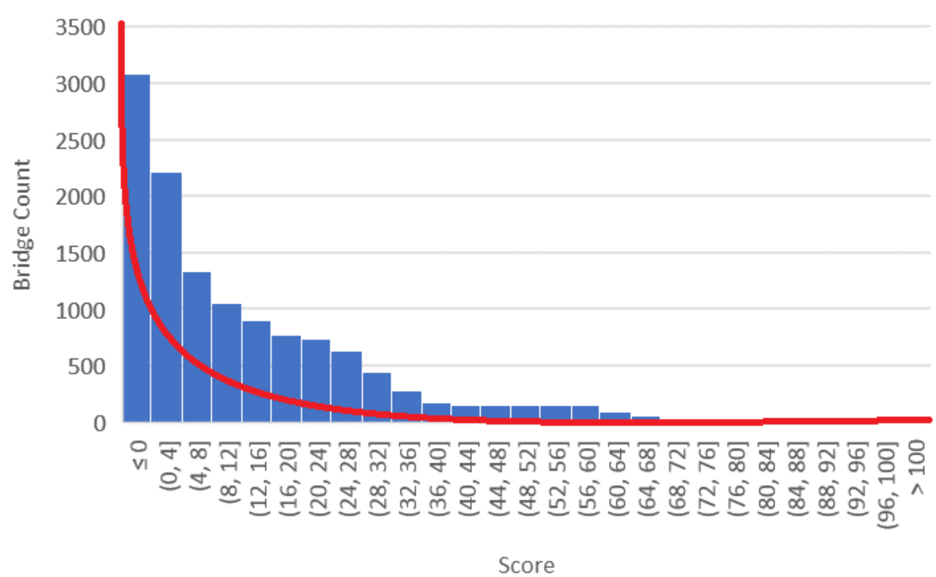


Figure A.3: Histogram of PRI Scores for Bridges Not Selected for Replacement

An analysis of the PRI score at the extents of the distributions reveals that only two of the bridges within the ten highest PRI scores are currently selected for replacement, as shown in Figure A.4. This analysis also reveals that the PRI does not utilize the full 120 point range when implemented in practice and that the majority of bridges are clustered at PRI scores below 30. While this would be acceptable if this skew was simply the result of proper classification of bridges not requiring replacement (which is the majority of bridges in the state) as low PRI structures, a comparative analysis of the number of bridges within the recommended ranges for qualitative classification of projects (Table A.4) reveals classification issues. As evidenced by Table A.4, there are more bridges that are not currently selected for replacement than those selected for replacement in both of the PRI ranges associated with "Very Good" and "Good" candidates. Collectively, this analysis supports the conclusion developed by NCDOT engineers that the PRI is an imperfect index for classification and prioritization of bridge replacement projects with numerous shortcomings.

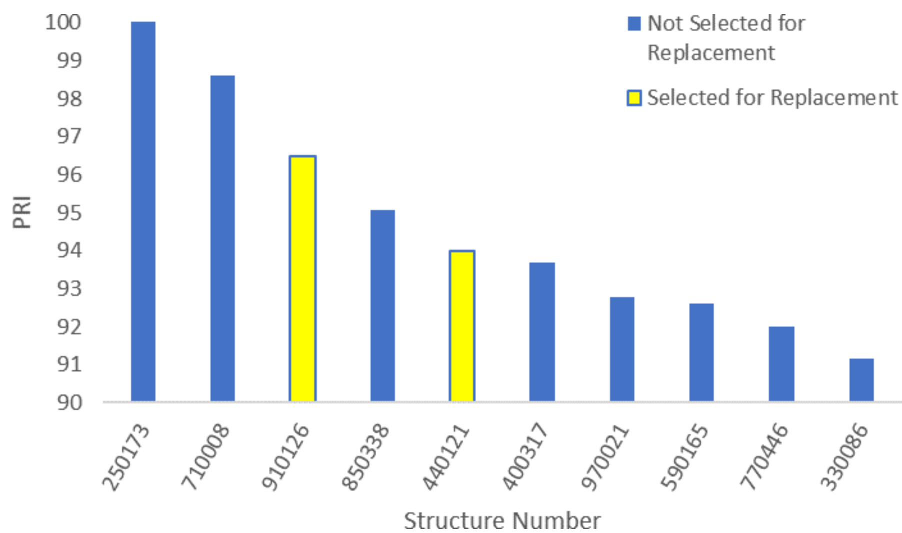


Figure A.4: Classification of Bridges with the Ten Highest PRI Values Currently in the State Inventory

Table A.4: Comparison of the Number of Currently Selected and Not Selected Bridge Replacement Projects by PRI Range

Replacement Candidacy	PRI Range	Selected	Not Selected
Very Good	PRI ≥ 50	537	588
Good	30 ≤ PRI < 50	409	1023
Poor	PRI < 30	303	10966

One suspected reason for the apparent shortcomings in the PRI is that it was developed as an ad-hoc index collecting several prior indices that were not originally designed to be utilized jointly. As a result, the PRI suffers from significant double-counting (and multiple-counting) of performance measures and does not present a clearly transparent view of how performance measures are individually weighted in computing the priority score. A count of the number of uses of each of the performance measures and the maximum potential contribution to the PRI by each measure was performed to illustrate these issues in the current index. Out of the 21 performance measures that are used for calculating the current PRI, seven suffer from either double, triple, or quadruple counting, as shown in Table A.5.

Table A.5: Multiple-Counted NBI Performance Measures in the PRI

NBI Item	Performance Measure	Count
29	ADT Over	4
19	Detour Length	3
51	Clear Deck Width	2
53	Vertical Clearance Over	2
58	Deck Condition	2
60	Substructure Rating	2
59	Superstructure Rating	2

An analysis of the maximum potential number of points that each performance measure can contribute to the PRI is presented in Figure A.5 which is adapted from Lane (2016). Since several equations in the PRI are either conditional or nonlinear, the actual contribution of each measure to the index is dependent on the individual bridge characteristics (which may be viewed as another shortcoming of the index). The analysis reveals that the ADT carried by the bridge has the largest potential impact on the PRI score by affecting as many as 72.62 points, while the Defense Highway Designation has the smallest potential effect with only a maximum effect on 1.76 points. Overall, this analysis indicates that the PRI score is dominated by the ADT and general condition ratings, while a large number of the 21 performance measures have relatively little impact on the PRI score.

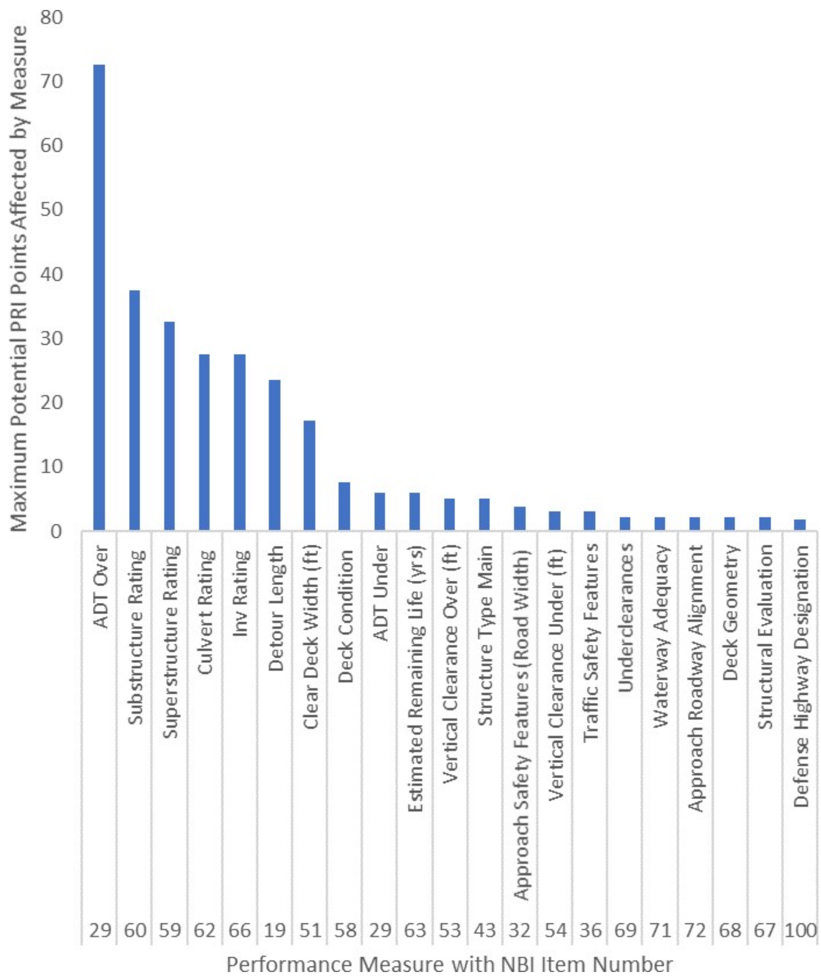


Figure A.4: Maximum Point Effect of Performance Measures in the PRI

In addition to double counting of performance measures, another potential reason for the shortcomings of the PRI is that this ranking system incorporates general condition ratings rather than element-level inspection data. General condition ratings aggregate the inspector ratings to form a single condition rating for each primary component of the bridge, but do not offer the same granularity of information on the location and extent of structural deterioration that element-level ratings do. Inspection and rating of bridges at the element-level has been mandated by the FHWA as part of the MAP-21 legislation (FHWA, 2012). A report on the improvements to bridge inspections nationally showed that the NBI served as the primary reporting system but did not include condition ratings that are granular enough for maintenance prioritization (Sobanjo and Thompson, 2016). The PRI only has three condition ratings that address the overall state of large parts of a bridge and do not give inspectors the ability to record the localized deterioration across the elements of the structure and substructure of a bridge.

Initially, the AASHTO Commonly Recognized Bridge Elements (CoRe) guidance was introduced as a system for element-level condition rating. In 2013, the AASHTO Manual for Bridge Element Inspection (MBEI) was released to provide a national standard for element inspection and recording (Farrar and Newton, 2014). Since 2014, NCDOT bridge inspectors have recorded element-level health ratings for each bridge to stay compliant with the FHWA inspection and recording requirements. Furthermore, using the element-level health ratings, a list of inspector recommended maintenance needs is developed for each structure. These tasks range from insignificant actions, such as removing deck debris and maintaining handrails, to major rehabilitation, such as replacing timber piles and repairing modular bridge joints. Ideally, a bridge with low maintenance needs should be considered a candidate for repair or rehabilitation instead of replacement. NCDOT has recently introduced the storage of new element-level condition rating data in their BMS as well as integrated the database of Inspector Recommended Maintenance Needs required to correct low element condition ratings for each structure. In this database, the element-level condition ratings for each structure are associated with specific maintenance actions for repair of each element and aggregated into total counts. Based on the condition rating of the elements, the corrective actions and counts are designated as either priority maintenance needs or recommended maintenance needs. Collectively this information allows for more detailed accounting of the type and number of elements requiring corrective action than the general condition ratings do and, further, provides a means for estimating the total cost of repairs.

A third shortcoming of the current PRI is that it does not consider the effects of maintenance history on the decision to prioritize replacement of a structure. Maintenance history is defined in this study as the maintenance actions that have been completed on each bridge and their associated costs. Maintenance history is likely to influence prioritization of bridge replacements in two ways. First, if the condition and rate of deterioration of a bridge has caused NCDOT to repeatedly perform maintenance year after year on the structure to maintain an acceptable level of service, then it is more likely to be a candidate for replacement. Such bridges present a maintenance burden that requires above average use of state resources and the cost-benefit ratio for such burdensome maintenance is unlikely to be a better economic decision than replacement. In contrast, bridges that have recently received major investments in either rehabilitation or preservation are less likely to be priority candidates for replacement, as returns on these investments in terms of increased service life are expected.

For a period of approximately ten years, NCDOT engineers have maintained a digital record of the number of maintenance actions performed on each bridge as well as the cost of each action. There are 12,299 bridges in North Carolina with recorded maintenance history that occurred within the past ten years. The average number of actions per bridge is 4.78 actions over ten years with a standard deviation of 4.51 actions. Overall, there are 58,832 recorded actions that were performed in the past ten years at an average of 5,454 actions per year. However, this maintenance history is not explicitly incorporated in the PRI or implicitly captured by any of the performance measures currently incorporated in the index.

A.3.4 NCDOT Research Needs

The STI law requires that all transportation projects funded through the state Highway Trust Fund or receiving funds from federal aid programs be prioritized by transparent and objective criteria. Although bridge replacement projects are exempt from the STI, movement towards performance-based project prioritization is needed to ensure progress towards this national effort which may expand to include bridge replacement projects in the future. Additionally, bridge project prioritization is a critical aspect of an effective BMS. Research to improve prioritization strategies and better balance the agencies preferences, network needs, and risk tolerances would result in more efficient use of NCDOT's annual budget allocated to bridge replacement and preservation.

NCDOT has found that the PRI has not consistently provided prioritization scores that align with the bridges that the bridge engineers choose for replacement. An initial analysis of the PRI index has revealed, among other issues: double- and multiple-counting of performance ratings, poor spread in the distribution of scores, and an observation that the calculation of the PRI is difficult to follow due to multiple sub-calculations that are specific to each performance measure. Ideally, a bridge replacement prioritization index should accurately reflect the preferences of the decision makers and follow a clear calculation methodology for transforming performance measure ratings to an overall priority score, neither of which are provided by the current prioritization index. An improved bridge replacement prioritization index would have the following characteristics:

- Transparent - Clear method of how a performance measure is converted into an overall replacement prioritization score.
- Data-Driven - Utilization of the NCDOT Bridge Management System (BMS) databases as well as the use of maintenance records.
- Normalized - Reduction of clustering of prioritization scores of bridges to allow bridges to be ranked effectively.
- Accurate - Results that reflect the engineers' preferences in regards to bridge replacement selections.
- Comprehensive - Contains all significant performance measures that drive the decisions of bridge engineers for bridge selection.

There is a need for NCDOT to utilize the optimization approach recommended in NCHRP Report 590, along with the extensive data available in the NCDOT AgileAssets BMS and input obtained from NCDOT personnel to develop useful guidelines and indices for prioritization of bridge replacement, rehabilitation, and preservation projects that comply with state and federal regulations, as well as incorporate local preferences and risk tolerances. As outlined in NCHRP Report 590, a select set of performance criteria and performance measures most significant for bridge prioritization in North Carolina needs to be identified. Performance criteria and performance measures need to appropriately reflect the agency's goals and recent policy targets, as well as comply with the spirit of new federal and state legislative requirements.

The key challenges that will need to be addressed in identifying appropriate performance criteria and measures include ensuring that the composite prioritization index formed from the performance metrics specifically balances: 1) completeness, to ensure that measures adequately reflect the extent that agency performance criteria are achieved; 2) simpleness, to ensure that the index is not cumbersome to implement and easily communicated to public stakeholders; 3) efficient in operational structure, to ensure that it can be computed readily using available information; and 4) non-redundancy, to ensure that the index is not biased due to double-counting of variables across metrics included in the composite index. Survey techniques need to be utilized to facilitate weighting of these performance criteria and measures to meet the relative importance and acceptable risk as perceived by stakeholder engineers and planners.

The goal of a bridge prioritization index is to determine a preference order of candidate bridge replacement projects to facilitate data-driven project selection. The preference order ranks bridge replacement projects that have a higher priority than other project selections with a specific point value. This value should reflect both the current condition of the bridge as well as other criteria and considerations that the engineers and decision-makers use when actually selecting and prioritizing structures for replacement.

When there are many criteria that have diverse or conflicting goals, one of the important factors is determining the trade-off in value between one selection candidate relative to another. One method to address the issue of developing clear and objective bridge project prioritization indices is through the use of value and utility functions within decision analysis, as outlined in NCHRP 590 (Patidar et al., 2007). A value function a mathematical model that reflects decision makers' preferences and provides a conversion of performance measure ratings into a normalized value (Patidar et al., 2007). The value functions for each of the performance measures are then combined into a single function, called a multi-criteria utility function. In this utility function, each criteria is weighted to reflect decision makers' preferences. This approach has been adopted in other bridge management systems (BMS) of other states including Indiana, California, and Virginia where multi-criteria utility functions have been developed and implemented to determine the criticality of bridges conditions (Sinha et al., 2009; Johnson, 2008; Moruza et al., 2016). The following sections of the literature review provide information supporting the research team's efforts to address these needs.

A.4 Performance Goals and Measures

NCHRP Report 590 presents clear, well defined guidance for states to enhance their bridge prioritization strategies. Many states have adapted methodology from NCHRP Report 590, or have a different prioritization model that is specific to their individual state needs. As outlined previously, new MAP-21 federal regulation requires each state to have a prioritization method that includes defined performance criteria and performance measures to be eligible for federal funding (FHWA, 2012). Although each state has a particular approach to bridge project prioritizations, methods vary based on states preferences, BMS capabilities, and other factors. In the following paragraphs, an overview of available literature on selected states' identification of performance goals and measures that reflect SHA preferences while meeting legislative requirements.

As part of a recent effort to enhance Colorado DOT's bridge prioritization strategies, researchers identified the prevalence of seven performance criteria used in bridge prioritization methods across the United States (Hearn et al. 2013). This review indicated that bridge condition and structural deficiency are the primary two performance criteria used by SHAs as performance measures for bridge project prioritization. A summary of the findings of Hearn et al. (2013) is presented in Table A.6, which resulted in proposed measures for bridge preservation for Colorado DOT. These performance measures for preservation use NBI general condition ratings together with DOT average cost data to assess the preservation impact (Hearn et al. 2013).

Table A.6: Performance measures for bridges (Hearn et al. 2013)

	MTKN	NCHRP 2024 (37) E	AASHTO Roundtable	BPETG Questionnaire
DOT Represented, count	36	39	33	17
Performance Measure Input	**Performance Measure Use**			
Bridge Condition	56.0%	56.0%	55.0%	64.0%
Bridge Program	33.0%	10.0%	18.0%	7.0%
Functional Obsolescence	14.0%	26.0%	15.0%	29.0%
Weight Restriction	3.0%	10.0%	18.0%	7.0%
Maintenance & Operations	22.0%	3.0%	12.0%	7.0%
Structural Deficiency	39.0%	56.0%	52.0%	50.0%
Sufficiency Rating	-	10.0%	9.0%	7.0%
Notes: MTKN = Midwestern Transportation Knowledge Network				
AASHTO = American Association of State Highway Transportation Officials				
BPETG = Bridge Preservation Expert Task Group				

Indiana DOT has historically had one of the more robust BMS in the United States, and a number of studies on the development and use of this BMS exist in the literature (Sinha et al., 1988; Saito and Sinha, 1989; Saito and Sinha, 1991, Sinha and Labi 2007; Li and Sinha 2009). Performance goals and measures utilized in the Indiana BMS are presented in Table A.7. Recently, Li and Sinha (2009) performed a study to determine relative weights of goals and performance measures. The Analytical Heirarcy Process (AHP) (discussed in Section A.5.1.3) was utilized to analyze survey data collected via the Delphi method (discussed in Section A.5.1.3) to determine the weights used in project prioritization. The authors concluded that the weighting process plays a "critical role" in multiple-criteria decision making for transportation infrastructure funding (Li and Sinha 2009).

Table A.7: Performance criteria and measures for Indiana (Li and Sinha, 2009)

System Goals	Performance Measures
System Preservation	Bridge structural condition
	Bridge wear surface condition
	Bridge remaining service life
Agency Cost	Bridge construction cost
	Bridge rehabilitation cost
	Bridge maintenance cost
Vehicle Operating Costs	Detour length
	Average travel speed
Mobility	Detour length
	Average travel speed
Safety	Bridge inventory rating
	Bridge clear deck width
	Bridge vertical clearance-over
	Bridge vertical clearance- under
	Bridge horizontal clearance

Other literature published about the Indiana BMS provides insight into the logic supporting decision making. In the Indiana BMS, each bridge is analyzed using a decision tree (DTREE) that determines the appropriate recommendation for each bridge to create a prioritization list. The DTREE (shown in Figure A.5) facilitates review of current bridge characteristics, recommends an appropriate repair or improvement activity, and then estimates the agency cost of that recommended action. Once this process is complete, the recommended projects from the DTREE are prioritized using the RANK model. This model uses four evaluation criteria (shown in Figure A.6), which are comprised of specific performance measures to determine which bridges are of greatest priority.

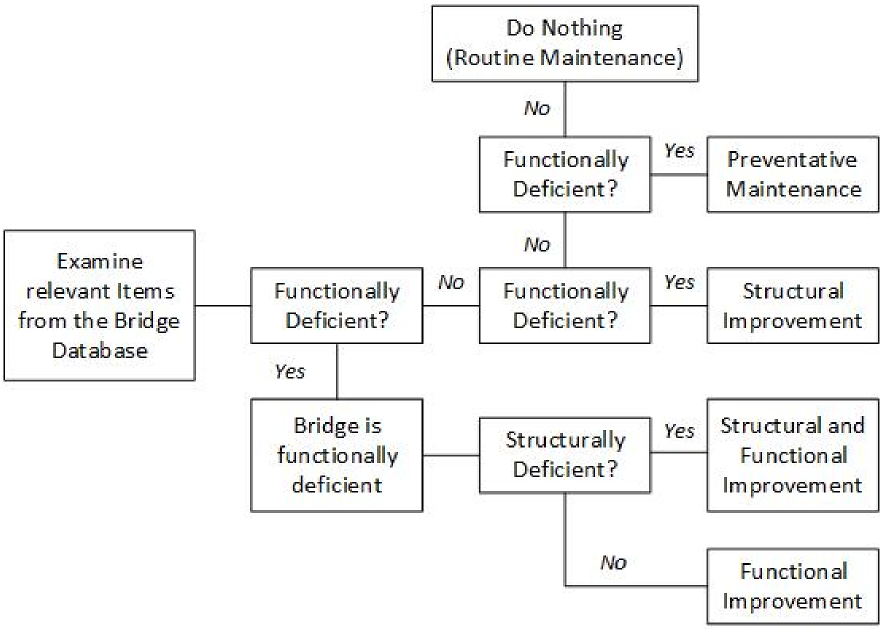


Figure A.5: DTREE (Sinha et al., 2009)

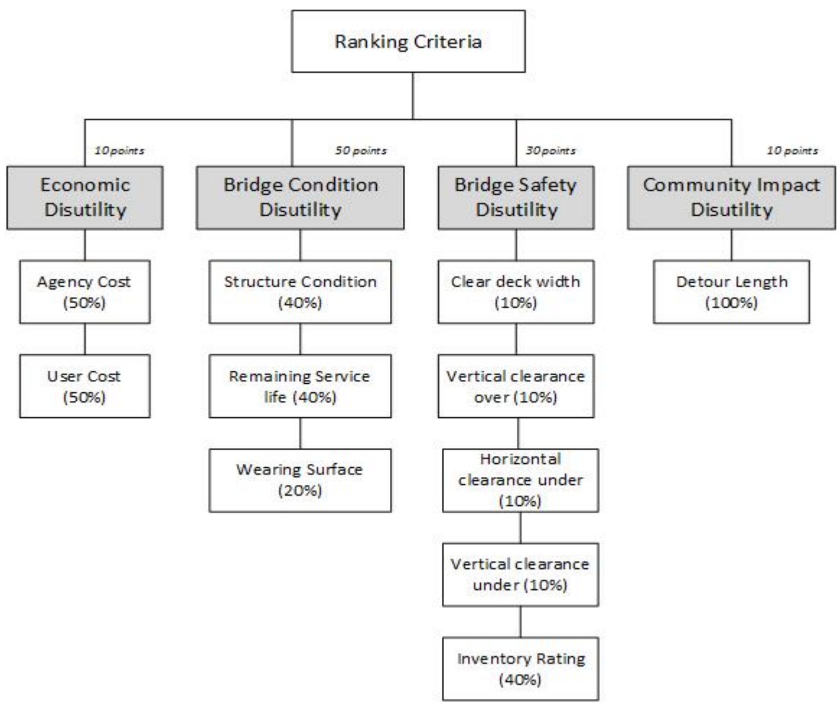


Figure A.6: Rank system (Sinha, et al. 2009)

California determines bridge project prioritization through a single utility formula (Johnson, 2008). This formula includes rehabilitation, scour, seismic, bridge rail upgrade, and mobility upgrades. The performance goals and measures are shown in Table A.6. Two of the five priorities (rehabilitation and mobility upgrades) can be measured using information contained in the state's BMS system. The other three priorities, scour needs, bridge rail upgrade needs, and seismic retrofit needs, are risk-based. The State Highway Operation Project Plan (SHOPP) utilizes the multi-objective utility theory to combine all five measures. The utility function is as shown in Equation A.7:

Table A.6: California's performance criteria and measures (Johnson, 2008)

Performance Criteria	Performance Measures
Rehabilitation and Replacement Needs	Bridge Health Index (BHI)
	Average Daily Traffic (ADT)
	Repair Urgency (U)
	Detour Length (DL)
Scour Needs	NBI Scour Code (SC)
	Average Daily Traffic (ADT)
	Detour Length (DL)
Bridge Rail Upgrade Needs	Caltrans Rail Upgrade Score (RS)
Seismic Retrofit Needs	Caltrans Seismic Priority (S_v)
	Average Daily Traffic (ADT)
	Detour Length (DL)
Mobility Needs (Raising / Strengthening)	Pontis Improvement Benefit (P)

$$U_t = a_1\beta_1X_1 + a_2\beta_2X_2 + a_3\beta_3X_3 + a_4\beta_4X_4 + a_5\beta_5X_5 \tag{A.7}$$

where: U_t = total project utility

a_i = binary operator used to express if the indicator that attribute is addressed or not

β_1 = rehabilitation or replacement weighting factor

X_1 = rehabilitation or replacement value coefficient

β_2 = scour weighting factor

X_2 = scour value coefficient

β_3 = rail upgrade weighting factor

X_3 = rail upgrade value coefficient

β_4 = seismic weighting factor

X_4 = seismic value coefficient

B_5 = raising and strengthening weighting factor

X_5 = raising and strengthening value coefficient

Each individual value function can contain multiple parameters. For example, for rehabilitation and replacement projects the utility function uses the Bridge Health Index (BHI), ADT volumes, detour length (DL), and repair urgency which is determined by the inspector. The average daily traffic (ADT) is the volume of traffic for the specific route the bridge carries. To determine the significance of each value using the parameters, the following formula is used:

$$X_i = 1 / (1 + e^{-C_i}) \tag{A.8}$$

where: X_i = the coefficient for each component of the utility
C_i = a function of the significant decision parameters for each value component

Table A.7 shows how the C for each value component is determined:

Table A.7: Variable C for value components (Johnson, 2008)

Utility Component	**Key Parameters**	**C_i**
Rehabilitation and replacement needs	BHI, ADT, repair urgency (U), and DL	-2.5 + 0.000001[(100-BHI-ΔBHI)TEV]/100+ 0.00000001 (ADT)(DL)+0.5(10-U)
Scour needs	NBI SC, ADT, and DL	-4 + (8-SC) + 0.0000001 (ADT)(DL)
Bridge rail upgrade needs	Caltrans rail upgrade score (RS)	-2 + RS
Seismic retrofit needs	Caltrans seismic priority (S_v), ADT, and DL	-1.5 + S_v + 0.000001 (ADT)(DL)
Mobility needs (raising / strengthening)	Pontis improvement benefit (P) (6)	-4.5 + 0.00015(P)

To determine the weights of each component, the bridge engineers performed a sensitivity analysis using the resulting component utilities and total project utilities. Table A.8 provides the results of this sensitivity analysis as weights for each component (Johnson, 2008).

Table A.8: Component weights (Johnson, 2008)

Attribute	**Weight**
Rehabilitation and replacement needs	25
Scour needs	20
Bridge rail upgrade needs	10
Seismic retrofit needs	25
Mobility needs (raising / strengthening)	20
Total	100

Similar to California's weighting system, New Jersey DOT and Ohio DOT use point based prioritization methods (Johnson, 2008; Bacheson et al. 2014; Ohio DOT, 2003). New Jersey's system uses the BMS performance criteria and measures provided in Table A.9. Currently, the model is based only on recordable measures and relies heavily on the sufficiency rating and structurally deficiencies. To refine this model, researchers are developing a way to incorporate risk (Section 2.4.3.5) (Bacheson et al., 2014).

Table A.9: New Jersey criteria weighting and scoring factors (Bacheson et al. 2014)

Criteria	Weighting (W)	Scoring (S)
Average Daily Traffic (Item 29)	10%	0 to 30,000 = 0 30,001-60,000 = 0.25 60,001 to 90,000 = 0.5 90,001 to 120,000 = 1.0
Functional Class (Item 26)	5%	Interstate / Freeways (01, 11, 12) = 1 Arterials (02, 06, 14, 16) = 0.67 Collectors (07,08, 17) = 0.33 Locals (09, 19) = 0
Deck (Item 58)	5%	3 or 4 = 1 5 or 6 = .5 >6 = 0
Sufficiency Rating	30%	(100-SR) / 100
Structurally Deficient	35%	Yes = 1, No = 0
Bypass Detour Length (Item 19)	5%	00 to 01 = 0 2-4 = 0.25 4-6 = 0.5 6-9 = 0.75 10 or more = 1
Scour Critical	5%	Yes (Code 3 or less) = 1 No = 1
Fracture Critical (Item 92A)	5%	Yes = 1, No = 0

Ohio DOT uses weighting factors for prioritization of locally owned major bridges that could be considered relatively simple compared to those used by other states. The local major bridges are funded and prioritized separately to ensure they are maintained and to help eliminate the impact on local agencies bridge programs (Ohio DOT, 2003). As shown in Table 2.15, Ohio DOT utilizes five performance criteria: general appraisal, sufficiency rating, local share, economic health, and regional impact. The point allocation and weightings are as shown in Table A.10 (Ohio DOT, 2003). The general appraisal rating is based on the inspection data which uses a 0-9 scale. Any bridge that scores over a 5 is acceptable and therefore not included in the prioritization for repair or replacement. The inspection point score is then converted to points for general appraisal as shown in Table 2.16 (Ohio DOT, 2003).

Table A.10: Ohio point allocations and weightings (Ohio DOT, 2003)

Category	Maximum Points	Weight Factor	Total Points
General Appraisal	10	3.0	30
Sufficiency Rating	10	2.0	20
Local Share Percent	10	1.0	10

Amount	10	1.0	10
Economic Health	10	1.5	12
Regional Impact	15	1.0	15
		Total Maximum Score	100

Table A.11: General appraisal points (Ohio DOT, 2003)

General Appraisal	Points
1-2	10
3	9
4	8
5	5
6-9	0

South Dakota DOT created a branch of their transportation department that determines how funding will be distributed to bridges. The Bridge Improvement Grant (BIG) provides the necessary funding to local governments for bridge projects. BIG uses a ranking criterion that is a combination of bridge condition, user impact, and local planning to allocate funding. It is based on a 100 point scale, as shown in Table A.12, similar to Ohio DOT, New Jersey DOT, Colorado DOT, and California DOT (SDDOT, 2015).

Table A.12: South Dakota's performance criteria and measures (SDDOT, 2015)

Performance Criteria	Performance Measure	Maximum Points
Bridge Condition	Posting	60
	Substructure Condition	
	Superstructure Condition	
	Culvert Condition	
	Fracture Critical	
	Scour Critical	
	Emergency	
	Sufficiency Rating	
User Impact	Average Daily Traffic	20
	Detour Length	
Local Planning	Wheel Tax	20
	Shovel Ready	
LPA Financial Commitment	Local match	Bonus points

In this section, the performance criteria, goals, and weighting used by several states to prioritize bridge projects has been presented. In the following sections, additional information about the performance criteria commonly utilized by many states is provided. Specifically, information regarding the performance measures utilized to assess the performance criteria, as well as sources of data used for these metrics, is detailed.

A.4.1 Infrastructure Condition

One of the most commonly utilized performance criterion used by SHAs for bridge project prioritization is bridge condition. As shown in Table A.6, over 55% of all SHAs consider the condition of the bridge in the prioritization process (Hearn et al. 2013). Typical performance measures include deck condition, superstructure condition, substructure condition, health index, and sufficiency rating (Patidar et al., 2007; Sinha et al. 2009). The NCHRP Report 590 recommends that performance criteria for condition preservation have a relative weight of 0.360 or 36%. In some states, such as Indiana, infrastructure condition can comprise as much as 50% of the overall score (Patidar et al., 2007; Sinha et al. 2009).

NCHRP Report 590 suggests three overall performance measures for measuring bridge condition: 1) Condition Rating, 2) Health Index, and 3) Sufficiency Rating. Each of these measures relies on inspection data, which describes the existing bridge condition relative to its original as-built condition. The rating is calculated by examining the materials and physical condition of the parts of the bridge, such as the deck, superstructure, and substructure. For the three performance measures suggested in NCHRP Report 590, the following condition ratings are considered: Deck Condition (NBI Item 58), Superstructure Condition (NBI Item 59), Substructure Condition (NBI Item 60), and Culvert Condition Rating (NBI Item 62). Each is rated on a 0 to 9 scale, with 9 signifying it is in perfect condition (Patidar et al., 2007).

The Health Index is a single number from 0 to 100, 100 being the best possible condition. This number is a reflection of the element level inspection data, in relationship to the asset value of a bridge (Patidar et al. 2007). Report 590 suggest utilizing the formula developed by researchers Shepard and Johnson (2001), who named this index the California Health Index. This Health Index is computed as follows:

$$HI = \left(\frac{\sum CEV}{\sum \mathrm{TEV}}\right) \times 100\% \tag{A.8}$$

$$TEV = TEQ \times W \tag{A.9}$$

$$CEV = W \times \sum(QCS \times WF) \tag{A.10}$$

$$WF = 1 - \frac{i-1}{State\ Count-1} \tag{A.11}$$

where: *HI* = health index,

CEV = current element value,

TEV = total element value,

TEQ = total element quantity,

QCS = quanitity in condition state 1,

WF = weighting factor for the condition state *i*, and

W = element weight.

The Sufficiency Rating has been described previously in this literature review, and eligibility for federal funding for bridge projects has been dependent on this score. The Sufficiency Rating utilizes four factors in computing a final numerical score. Higher Sufficiency Rating scores indicate better bridge conditions, with 100% being the best score possible. A lower score indicates poorer bridge condition, and therefore the higher likelihood for selection for funding.

NCHRP report 590 suggest relative weights for each performance measure. The suggested relative weights for NBI condition ratings are 0.271 or 27.1%, with each condition being about 0.33 or 33% of the 27.1%. The suggested weight for health index is 0.507 or 50.7%, and the suggested weight for sufficiency rating is 0.222 or 22.2%. Together the measures are added together to create bridge preservation performance criterion of the prioritization score. The sufficiency rating is calculated as (FHWA, 1995):

$$SR = S_1 + S_2 + S_3 + S_4 \tag{A.12}$$

Where the four factors are as follows:

1) Structural Adequacy and Safety (S_1): 55% Max
   (Superstructure, substructure, culverts, inventory rating)
2) Serviceability and Functional Obsolescence (S_2): 30% Max
   (Lanes on structure, average daily traffic, approach roadways width, structure type, bridge roadway width, vertical clearance over deck, deck condition, structural evaluation, deck geometry, under-clearance, waterway adequacy, approach roadway alignment, highway designation)
3) Essentiality for public use (S_3): 15% Max
   (Detour length, average daily traffic, highway designation)
4) Special Reductions (S_4): 13% Max
   (Detour length, traffic safety features, structure type)

Similar to the approach outlined in NCHRP Report 590, Indiana DOT uses a single weighted equation that combines three overarching performance measures to determine the bridge condition disutility, as shown in Equation A.13. The equation includes structural condition disutility, wearing surface, and remaining service life. The structural condition disutility is determined by the minimum value of the three NBI condition rating values: deck, superstructure, and substructure condition. The estimated remaining service life is computed as the difference between the expected service life and the current age of the bridge. Lastly, the wearing surface is defined by the condition of the wearing surface. This approach used by Indiana is unique in that it uses decision analysis to incorporate preference and risk into the disutility function.

$$U_{COND} = w_{SCR}U_{SCR} + w_{RSL}U_{RSL} + w_{WSCR}U_{WSCR} \tag{A.13}$$

where: U_{COND} = overall disutility value for the bridge condition
w_{SCR} = importance weight for structural condition rating
U_{SCR} = disutility value for the structural condition rating

w_{RSL} = importance weight for remaining service life
U_{RSL} = disutility value for remaining service life
w_{WSCR} = importance weight for wearing surface condition rating
U_{WSCR} = disutility value for wearing surface condition rating

South Dakota's BIG ranking criteria also includes a bridge condition component. The BIG system computes priority on a scale of 100 points, with bridge condition being worth up to 60 points of the total 100. Bridge condition is scored using eight performance measures (SDDOT, 2016):

a) Posting (29 max points) - As defined by NBI Item 70 and Table A.13.

Table A.13: Posting rating (SDDOT, 2016)

Bridge Inventory Code	Relationship of Operating Rating to Max Legal Load	Ranking Points
5	No Posting Required	0
4	0.1 to 9.9% Below	6
3	10.0 to 19.9% Below	12
2	20.0 to 29.9% Below	18
1	30.0 to 39.9% Below	24
0	> 39.9% Below	29

b) Substructure Condition (6 points max) – As defined by NBI Item 60, with ranking points assigned as shown in Table A.14.
c) Superstructure Condition (6 points max) – As defined by NBI Item 59, with ranking points assigned as shown in Table A.14.
d) Culvert Condition (12 points max) – As defined by the NBI Item 62, with ranking points assigned as shown in Table A.14.

Table A.14: Condition rating (SDDOT, 2016)

Bridge Inventory Code	Ranking Points
>5	0
5	1
4	2
3	3
2	4
1	5
0	6

e) Fracture Critical (6 points or zero points) – Points awarded if structure is determined to be Fracture Critical
f) Scour Critical (6 points or zero points) – Points awarded if structure is determined to be Scour Critical
g) Emergency (6 points or zero points) – Points awarded if structure has been closed due

to a catastrophic failure not eligible to receive Federal Emergency Management Agency or FH Emergency Relief Fund

h) Sufficiency Rating:

$$(1 \text{ point max}) - (100 \times SR) / 100 \tag{A.14}$$

One of the simplest bridge condition formulae was developed by the Oregon Department of Transportation. It addresses bridge condition by looking at Key Performance Measures, known as KPM 16, which are divided into two categories, structurally deficient and other deficiencies (ODOT, 2015). A bridge is determined to be structurally deficient in accordance with the NBIS formula, based upon the level of deterioration in the deck, substructure or superstructure. The "other deficiency" category is made of three criteria: freight mobility needs, bridge safety needs, and serviceability needs. Freight mobility uses load capacity (NBI Item 67), vertical clearance (NBI Item 53), and geometric clearance (NBI Item 43) as performance measures. Bridge safety needs include scour (NBI Item 113) and bridge rail (NBI Item 26) deficiencies as performance measures. Serviceability needs incorporates painting needs, cathodic protection, movable bridge repairs, and remaining service life as measures. The other deficiency score is combined with the sufficiency rating score to create a final bridge condition score (ODOT, 2015).

Ohio also includes sufficiency rating as one of the factors for prioritization. Sufficiency rating accounts for 20 points out of 100 for the total prioritization score. The sufficiency rating is calculated using the FHWA's Recording and Coding Guide for the Structure Inventory and Appraisal of National's Bridges, the formula used to compute points for ODOT's prioritization formula is as follows (Ohio DOT, 2003):

$$\text{Points} = (100 - \text{Sufficiency Rating}) / 10 \tag{A.15}$$

where: if the point calculation is less than 2.0, the points assigned will be 0.
if this category has a weight factor of 2.0, then it has a maximum total point value of 20.

A.4.2 Benefit-Cost

Benefit-Cost is computed in order to compare the relative benefits achieved by performing a project to its cost. This type of analysis aids in determining if the project is an economically attractive investment, and can be used to compare cost with other alternative projects. Often, benefit-cost analysis is performed on a project basis, but has occasionally been used in bridge prioritization on a network level. There are several approaches to benefit-cost analysis that can be used, including the benefit/cost ratio, net present value, cost-effectiveness, internal rate of return, and payback period (Dahlgren et al. 2004). The approach to benefit-cost analysis selected often depends on what type of information (or comparison) is being sought and the information available to support the analysis.

Historically, Kentucky DOT utilized benefit-cost ratio in the 1980's to rank deficient bridges (Hopwood and Oka 1989). Research performed during that decade supported the development of an annual net benefit (in dollars) system for ranking bridge projects. This approach, computed using the annual worth of total benefits obtained by "Improving a bridge less the cost of that improvement on an annual basis," was deemed an approach that met needs and intent, while also having the benefit of being computed in the easily understandable metric of monetary value (Hopwood and Oka 1989).

In more recent years, benefit-cost has been considered by SHAs in project prioritization using different approaches. It is noted that guidance provided in NCHRP Report 590 does not include a designated performance criterion associated with benefit-cost. It does, however, include recommendations of the performance criteria of agency cost minimization and user cost minimization. Agency cost includes initial cost and life-cycle agency cost performance measures. User cost minimization looks at only life-cycle user cost (Patidar et al. 2007), and reduction of user costs could be seen as a benefit of a bridge improvement or replacement project.

Vermont Agency of Transportation (VTrans) uses the performance criterion of Asset Benefit-Cost Factor. It compares the benefit of keeping a bridge in service to the cost of constructing a new one. It is worth a total of 10 points on a 100 point prioritization scale (VTrans, 2015). Michigan DOT assesses benefits and costs associated with project prioritization on a broader scale, with their model having two components: corridor projects and interchanges (MDOT, 2014). Other states include performance measures similar to those suggested in NCHRP Report 590, but also associate them with the criteria of user impact and economic disutility, not benefit-cost. For example, in South Dakota, in the criterion User Impact, a total of 20 points that are allocated based on the impact on the user, which is assessed using the average daily traffic and detour length. The following equations are used to determine the user impact (SDDOT, 2016):

$$\text{User Impact (On-System)} = \text{ADT} \times \text{Detour Length (miles)} / 350 \quad \text{(A.16)}$$

$$\text{User Impact (Off-System)} = \text{ADT} \times \text{Detour Length (miles)} / 100 \quad \text{(A.17)}$$

Lastly, South Dakota DOT allocates a maximum of 20 points to local planning, based on the wheel tax and if the project is shovel ready. The wheel tax has a maximum of 10 points and is calculated as shown in Table 2.20. "Shovel ready" is allocated a maximum of 10 points, and is determined by whether the project is ready to be started within 6 months of the grant being awarded. There are bonus points available with the LPA Financial Commitment which allocates three points for every 5% of increased local funding match beyond the required 20% (SDDOT, 2016).

Table A.15: Wheel tax point calculation (SDDOT, 2016)

Assessment / Wheel	Point
$5	10
$4-$4.99	Actual $ Amount x 2
$3-$3.99	Actual $ Amount x 2

\$2-\$2.99	Actual \$ Amount x 2
\$1-\$1.99	Actual \$ Amount x 2
\$0-\$0.99	0

Indiana's approach to measuring benefit-cost using utility theory is based on agency cost and user cost disutility functions. The overall prioritization score is out of 100 points, of which 10 are allocated to economic disutility. Agency cost is worth 50% of the total allocated point values. The agency cost disutility is calculated from the Cost Effectiveness Factor (CEF). It is expressed as "the product of deck area and traffic volume that is served in a year by a dollar of agency cost investment...the reciprocal function of the equivalent uniform annual AGENCY cost required to serve one vehicle per day unit deck (Sinha et al. 2009)." Computation of the CEF is shown below in equation A.18.

$$CEF = \frac{365 \times ADT \times BL \times Total\ Deck\ Width}{EUAC_{\infty}} \quad (A.18)$$

where: CEF = Cost Effectiveness Factor
ADT = Average Daily Traffic
BL = Bridge Length
$EUAC_{\infty}$ = Equivalent Uniform Annual Agency Cost

The CEF includes deck area and traffic volume to normalize the "economic efficiency evaluation criteria." The CEF is defined using the lowest and highest value for all projects considered to reflect the range of costs, ages, and traffic volumes. If a project's CEF is equal to the highest CEF for those under consideration, it is assigned a disutility of 0; if it is the lowest it is assigned a disutility of 100. All others are in-between the highest and the lowest are pro-rated appropriately (Sinha et al. 2009).

User cost is 50% of the 10 points for the economic disutility scored by Indiana DOT. The user cost disutility corresponds to the equivalent uniform annual user cost, and is computed as shown in equation A.19. For overall economic efficiency disutility, the "algebraic sum of the agency cost disutility and the user cost disutility (Sinha et al. 2009) is measured as shown in equation A.20.

$$U_{UC} = EUAUC \text{ or } EUAC_{UC,\infty} \quad (A.19)$$

where: U_{UC} = user cost disutility
$EUAUC$ = equivalent uniform annual user cost in perpetuity

$$U_{econ} = U_{AC} + U_{UC} \quad (A.20)$$

where: U_{econ} = Economic Efficiency Disutility

U_{AC} = Agency Cost Disutility
U_{UC} = User Cost Disutility

Currently, the performance measures incorporated into the NCDOT PRI do not include benefit-cost. Since MAP-21 addresses broad national goals related to network-level performance rather than specific criteria for optimal decision-making in transportation investments, no performance measures related to benefit-cost are associated with MAP-21. However, the STI legislation includes benefit-cost as one key performance criterion. NCDOT P5.0 defines the benefit-cost criterion as "the expected benefits of the project over a 10-year period against the estimated project cost to the NCDOT" (NCDOT, 2018). Computation of the Benefit-Cost using the P5.0 methodology is as shown in equation A.21.

$$\left[\frac{(Travel\ Time\ Savings\ over\ 10\ years\ in\ \$ + Safety\ Benefits\ over\ 10\ years\ in\ \$)}{Project\ Cost\ to\ NCDOT\ at\ time\ of\ submittal}\right] + \left[\frac{Other\ Funds}{Total\ Project\ Cost} \times 100\right] \qquad (A.21)$$

The first term of equation A.21 is essentially user costs divided by agency costs. Travel time savings can be computed using several approaches supported by NCDOT, including the North Carolina Statewide Travel Demand Model (NCSTDM) for statewide mobility & regional impact corridor projects. Safety benefits are computed using a safety benefit factor multiplied by existing crashes (monetized by crash severity). Project costs include agency costs associated with construction, right-of-way, and utility costs. As shown in the second term of equation A.21, costs can be lowered and the score increased if other (non-project) funds such as local funds and tolls are committed (NCDOT, 2018).

A.4.3 Safety

The performance criterion of safety, as defined by MAP-21, is to "achieve a significant reduction in traffic fatalities and serious injuries on all public roads" (FHWA, 2012). Based on a review of literature, this criterion is often indirectly measured, with functional deficiencies typically linked to traffic safety (such as clear deck width, vertical clearance, and horizontal clearance) measured in lieu of actual data on bridge-related crashes, such as the number or severity.

NCHRP Report 590 suggests the general goal of Traffic Safety Enhancement, using the performance measures of geometric rating divided by functional obsolescence and inventory rating or operating rating (Patidar et al. 2007). Geometric rating (NBI item 68) is a combination of the overall rating for the deck geometry based upon the bridge roadway width (NBI Item 51) and vertical over-clearances (NBI Item 53). The rating scales from 0 to 9, with 9 being in the best condition. Inventory rating (NBI Item 66) is a representation of the design standard and amount of load a given bridge can safely support at its given state for an indefinite period of time. The rating is designated by a three-digit number, determined by the total mass in tons of the entire vehicle measured (Patidar et al., 2007).

Similar to the guidance provided in NCHRP Report 590, other states such as Indiana also have functionality performance measures utilized to indirectly measure the safety performance criterion. In INDOT's BMS, these measures include those based on spatial adequacy and structural integrity: clear deck width, vertical clearance, horizontal clearance under, vertical clearance under, and inventory rating. Spatial adequacy relates to vehicle safety and while structural integrity is associated with the risk of the structure failing.

Bridge safety disutility can contribute up to 30 points out of the total 100 points for the ranking formula. Of the 30 points allotted to the bridge safety disutility, clear deck width is weighted at 30%, vertical clearance over the bridge is weighted at 10%, horizontal clearance under the bridge is weighted at 10%, vertical clearance under the bridge is weighted at 10%, and the inventory rating is weighted as 40% (as seen in Figure 2.5) (Sinha et al., 2009).

The structural integrity is determined by the inventory rating. The lower the inventory rating, the greater the risk of failure. Therefore, a higher disutility is given to bridges with low inventory ratings. If a bridge has an inventory rating of 36 tons or greater, then no disutility is assigned. Equation A.22 shows computation of the disutility value for safety objectives used by Indiana (Sinha et al., 2009):

$$U_{SAFTEY} = W_{CDW}U_{CDW} + W_{VC}U_{VC} + W_{HR}U_{HR} + W_{IR}U_{IR} \tag{A.22}$$

where: U_{SAFTEY} = Disutility value for safety objective

U_{CDW} = Disutility value for clear deck width
U_{VC} = Disutility value for vertical clearance
U_{HR} = Disutility value for horizontal clearance
U_{IR} = Disutility value for inventory rating
W_{CDW} = Importance weight for clear deck width
W_{VC} = Importance weight for vertical clearance
W_{HR} = Importance weight for horizontal clearance
W_{IR} = Importance weight for inventory rating

Recently following MAP-21, national performance measures for safety have been introduced specifically for the STI. These measures are: 1) number of fatalities, 2) rate of fatalities (per vehicle mile travelled), 3) number of serious injuries, and 4) rate of serious injuries. Computed as 5-year rolling averages, these measurements are calculated over the entirety of the state using the National Safety Council's KABCO coding convention for severity.

Although NCDOT does not directly use crash data in the PRI, related performance measures are used for prioritizing other types of infrastructure projects, as outlined on NCDOT's Prioritization Resources website (NCDOT, 2019).

In the NCDOT P5.0, the safety performance criterion is identified by using crash information for a given highway segment. Crash density (20%), crash severity (20%), critical crash rate (20%) and safety benefits (40%) are used in prioritization of roadway projects, with the associated weights shown in parentheses. The crash frequency and severity index are used in prioritization of highway intersection projects, with each accounting for 30% of the safety measure weight, along with 40% weight allocated to safety benefits (NCDOT, 2018).

A.4.4 Congestion Reduction

Congestion reduction is a performance criterion focused on efforts to significantly reduce the congestion of a particular road system, and is among the national performance criteria included in MAP-21 (Dahlgren et al. 2004). However, review of literature indicates that outside of new strategic programs for prioritization of general transportation projects in a few states such as Florida and Ohio (Ohio DOT, 2003; FDOT, 2012), congestion reduction has not been specifically linked to a performance criteria for bridge project prioritization within other states. NCHRP Report 590 does not specifically include a performance criteria or performance measure for congestion reduction. However, in the sufficiency rating under the condition preservation, ADT is a considered measure (Patidar et al., 2007).

Similar to the recommendations provided NCHRP Report 590, Ohio and Georgia do not state a specific goal of congestion reduction, but consider the regional impact using ADT as a primary performance measure (Ohio DOT, 2003; Amekudzi and Meyer, 2011). The regional impact factor for Ohio DOT accounts for an individual bridge's significance to an area. The points are determined by the average daily traffic, detour length, and functional class. The points are allocated as shown in Table A.16 (Ohio DOT, 2003). New Jersey accounts for congestion by weighting specific performance measures by average daily traffic (Szary and Roda, 2014).

Table A.16: ADT, detour length, and functional class point allocation (Ohio DOT, 2013)

ADT	Points	Detour Length	Points	Functional Class	Points
>40,000	5	>5	5	Principal Arterial (1,2,11,12,14)	5
>30,000-40,000	4	4	4	Minor Arterial (6,16) Collector (7,17)	3
>20,000-30,000	3	3	3	Local (9,19)	1
>10,000-20,000	2	2	2		
<10,0000	0	0 to 1	0		

In NCDOT Prioritization 5.0, congestion reduction for projects subject to STI prioritization is determined by measuring "the existing level of mobility along roadways by indicating congested locations and bottlenecks." NCDOT includes both existing volume/capacity ratio and existing volume as performance measures for both statewide mobility and regional impact. The weights of existing volume/capacity ratio and existing volume are 60%/40% for statewide mobility projects and 80%/20% for regional impact projects. Only existing volume/capacity ratio is used for division needs projects (NCDOT, 2018). As stated previously, bridge projects are not subject to STI prioritization, and these measures do not directly apply.

A.4.5 Vulnerability

Vulnerability is not mentioned in MAP-21 federal guidelines, the STI legislation, or NCDOT P5.0. However, vulnerability is a focus of a portion of the NCHRP Report 590, which recommends that vulnerability be incorporated into risk-based prioritization of bridge replacement projects. When a bridge is vulnerable, it has characteristics that can present hazards that make it susceptible to damage, such as poor design or inadequate preventative maintenance. The primary goal of measuring vulnerability is to determine how likely a bridge could be effected by extreme weather or natural event. NCHRP Report 590 suggests the following performance measures (Patidar et al., 2007):

1) Scour Vulnerability Rating
2) Fatigue/ Fracture Criticality Rating
3) Earthquake Vulnerability Rating
4) Other Disaster Vulnerability Rating (Collision, Overload, and Human-Made)

These general vulnerability measures suggested in Report 590 were adopted from NYSDOT (1996). It is based on the likelihood and effect of an event, as seen in Figure A.7. To measure the likelihood of an event, there is a classification process that is specific to the "type of vulnerability considered." The effect of a failure is based on the type of failures the bridge is prone to and how the failure would affect the public. Using a general vulnerability score table (Table A.17), users can assign risk for each vulnerability types. The vulnerability score is defined as:

$$\textit{Vulnerability Rating} = \textit{Likelihood Score} + \textit{Consequence Score} \tag{A.23}$$

where: *Consequence Score* = Failure Type Score + Exposure Score
Exposure Score = Traffic Volume Score + Functional Classification Score

The score is converted to a rating between 1 and 5 associated with the following definitions shown in Table A.18.

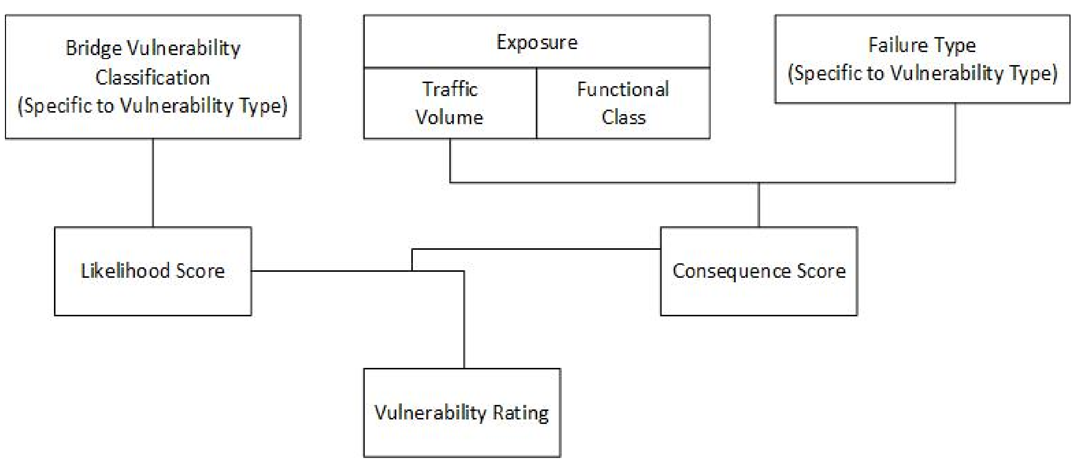


Figure A.7: Vulnerability consideration (NYSDOT, 1996)

Table A.17: General vulnerability score (Patidar et al., 2007)

Vulnerability Class	**Likelihood Score**
High	10
Medium	6
Low	2
Not Vulnerable	0
Failure Type	**Failure Type Score**
Catastrophic	5
Partial Collapse	3
Structural Damage	1
Traffic Volume	**Traffic Volume Score**
>25,000 AADT	2
4,000-25,000 ADT	1
<4,000 AADT	0
Functional Classification	**Functional Classification Score**
Interstate Freeway	3
Arterial	2
Collector	1
Local Road & Below	0

Table A.18: Score conversions (Patidar et al., 2007)

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

Scour vulnerability rating is divided into two components: general hydraulic assessment and foundation assessment. For each of these assessments, specific parameters for each are examined and assigned a value. For foundations, all abutments and piers on the structure are examined, but the one with the most critical score is used. The final score is used to determine a high, medium, or low vulnerability rating. In Figure A.8 the representation of this process is graphically illustrated (Patidar et al. 2007).

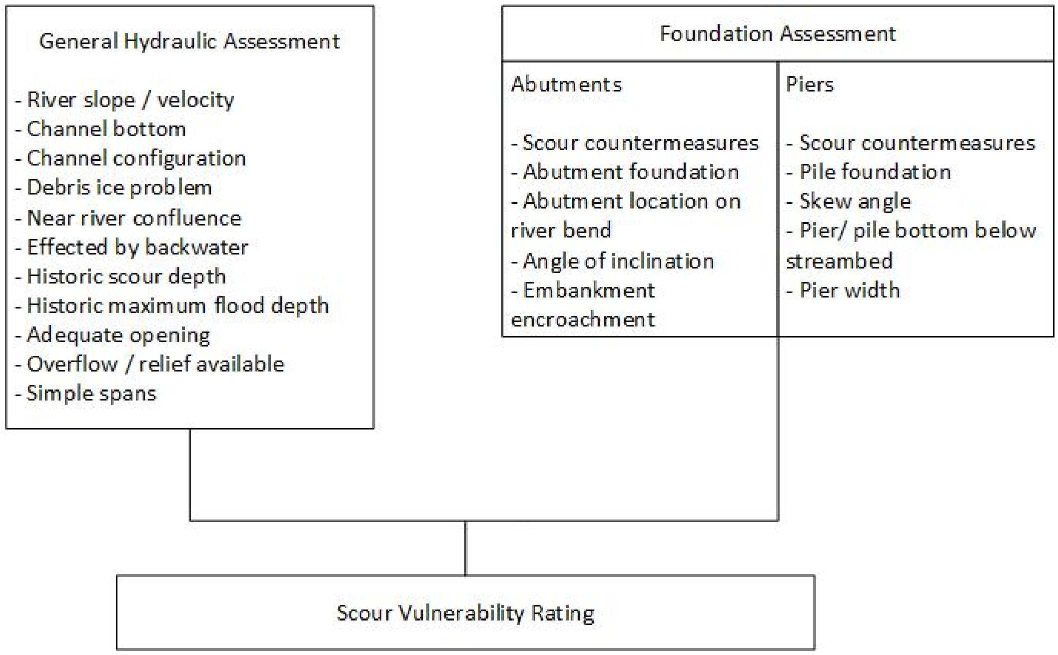


Figure A.8: Scour vulnerability rating (Patidar et al. 2007)

Other states have factored vulnerability into their prioritization of bridge projects. For example, as stated previously, California is concerned with preservation in five areas, two of those being vulnerability-related (scour and seismic risk potential). Along with bridge rail upgrades, these three areas are the only risk-based programs and account for approximately 40% of all of the State Highway Operation Protection Plan's (SHOPP) budget for bridges. Scour needs assessments comprise 20% of the prioritization score for bridges, and seismic retrofit needs comprise 25%. To determine which bridges will receive prioritization, a primary condition rating is used, as described in Section A.4. However, the condition rating is also combined with a risk assessment to determine a final weighted utility (Johnson, 2008). This helps decision-makers evaluate whether one bridge can provide more utility benefits over another. Table A.19 shows a comparison of two bridges using this method (Johnson, 2008):

Table A.19: Bridge utility rating (Patidar et al. 2007)

Structure	**Score Risk (NBI Item 113)**	**Scour Value Coefficient**	**Condition Value Coefficient**	**Total Utility (weighted sum of coefficients)**
Bridge A	Scour Critical – 3	0.75	0.20	0.25(0.20)+0.20(0.75) = 0.20
Bridge B	No Scour – 8	0.00	0.20	0.25(0.20)+0.20 = 0.05

Utah utilize vulnerability and criticality to influence the ranking of the most vulnerable bridge structures. The vulnerability rating is a total of 100 points and includes both BHI Score and operating load rating score. The BHI has a maximum of 75 points and the operating load rating score (LRS) has a maximum of 25 points. The formula for vulnerability is provided in Equation A.24 (UDOT, 2014).

$$\text{Vulnerability Score} = 0.75(\text{BHI}) + \text{LRS} \tag{A.24}$$

The LRS is directly dependent on the load rating for each bridge, any bridge with a load rating greater than 1.0 receives a LRS of 25. Any structure with a rating equal to or lower than 0.3 receives a LRS of 0. For a bridge with a rating anywhere between 0.3 and 1.0, equation A.25 is used to determine its rating score (Bridge Management Manual, UDOT, 2014):

$$\text{LRS} = (\text{LR} - 0.3) / 0.028 \tag{A.25}$$

where: *LRS* = Load Rating Score
LR = Load Rating

The criticality score is a sum of individual scores derived from specific performance measures, including average daily traffic, significance factor, and time to restore-delay factor. The scores are shown in Table A.17. The significance factor is based on the length of the detour that would need to be utilized in the case of an out-of-service bridge. This factor helps to ensure that low AADT bridges are not overlooked when being compared to high AADT bridges and routes (UDOT, 2014). The impact categories and scores for bypass length are shown in Table A.20. Finally, the time to restore-delay factor is accounted for and is a measure of the cost of downtime from not having a bridge in service. This measure assumes the time based upon the overall length of the bridge (Table A.21) (UDOT, 2014).

Table A.20: Bypass length score factor (UDOT, 2014)

Impact	Bypass Length	Score
No direct impact	Less than 1 mi	2
Minimal (local or regional)	1-4.9mi	8
Moderate (local or regional)	5-14.9mi	16
Significant (local or regional)	15-24.9mi	24
Severe (statewide)	25-34.9mi	32
Extreme (local or regional)	More than 35mi	36

Table A.21: Bridge length score factor (Bridge Management Manual, UDOT, 2014)

Overall Bridge Length	Score
<20’	0
>20’ but <60’	7
>60’ but <150’	14
>150’ but <200’	21
>200’	28

New Jersey DOT has developed a Risk Based Prioritization Method to determine vulnerabilities (Adams et al. 2014). It incorporates four parts: limit state (geotechnical, hydraulic safety, structural safety, serviceability, and durability or operations), risk component (hazard, vulnerability, or exposure), typical range or condition classification, and point value. Each bridge is categorized into a limit state, for example structural safety, from there the hazards, vulnerabilities, and exposures are identified and given a point value. The hazard, vulnerability, and exposure are multiplied to define the total aggregated risk. A bridge can combine multiple limit states using the formula shown in equation A.26. Each risk value is normalized on a 100 point scale which then is used to classify the risk value into one of the five categories (Table A.22).

$$Combined\ Risk = \sqrt{Geo/HydraSafety^2 + Structural\ Safety^2 + Service\&Duribility^2 + Operations^2} \tag{A.26}$$

Table A.22: Risk values (Adams et al., 2014).

Risk Level	Risk Value Range
Severe	80-100
High	60-80
Elevated	40-60
Guarded	20-40
Low	0-20

A.4.6 Economic Competitiveness

Economic competitiveness (or economic vitality) is a measure of how a bridge project will impact the local community. Economic competitiveness is typically measured indirectly using user costs associated with detours around deficient or closed bridges, since detours cause travel time delays, additional transportation costs, and impact to local businesses and industry (Chen and Johnson, 1987). Although the MAP-21 legislation indicates that economic competitiveness is a national goal, federal guidelines do not propose specific performance measures related to economic competitiveness. However, some states, including North Carolina do include economic competitiveness as a performance criteria in their prioritization process. NCHRP Report 590 also does not propose a specific performance criterion related to economic competitiveness, but does suggest inclusion of user cost in optimization methodologies (Patidar et al., 2007).

One SHA with bridge project prioritization practices that include a performance criterion focused on economic competitiveness is Ohio. ODOT's Economic Health performance criterion is used to achieve a measure of equality between areas that have unequal financial wealth. The economic health of an area is determined by the level of economic distress of Ohio local governments, which is determined by the unemployment rate of the project sponsor (municipality or the county). Points associated with this measure are allocated as shown in Table A.23 (Ohio DOT, 2003):

Table A.23: Unemployment rate point allocation (Ohio DOT, 2003)

Local Agency's Unemployment Rate in Relation to the Statewide Rate	Points
30.1% or greater than statewide rate	10
25.1%- 30% greater than statewide rate	8
20.1%- 25% greater than statewide rate	6
10.1% -20% greater than statewide rate	4
0.1% - 10% greater than statewide rate	2
Equal to or below statewide average	0

Vermont Agency of Transportation (VTrans) includes the performance criterion of Regional Input and Priority in its bridge prioritization. Points are allocated towards this criterion if the local planning commission supports a project for both local land use and economic development. Regional Input and Priority is worth a total of 15 points out of a 100 point prioritization calculation (VTrans, 2015).

As mentioned previously, NCDOT currently does incorporate economic competitiveness into transportation project prioritization for projects subject to the STI, since STI legislation has established economic competitiveness as one of the performance criteria. In NCDOT's P5.0, the performance criterion of economic competitiveness is defined as "the economic benefits the transportation project is expected to provide in economic activity and jobs over 10 years" (NCDOT, 2018). Two performance measures are currently used for project subject to STI prioritization: percent change in county economy and % change in long-term jobs. The score is computed using the TREDIS transportation economic impact model, which is utilized by entities across the US, Canada, and Australia (including the states of Idaho, Kansas, Ohio, Nebraska, Wisconsin and others). The TREDIS model utilizes data on transportation improvement projects to compute travel benefits, household/industry response and changes in access, and ultimately economic growth (impact). This criterion does not include contingent (or prospective) development (NCDOT, 2018).

A.4.7 Multimodal, Freight, and Military Mobility

Freight mobility and economic vitality are addressed together in MAP-21 federal performance criteria, since a national goal of freight movement is proposed in this legislation. This goal is to improve the freight network in order to strengthen community access to national and international trade markets and to help support economic development. "Multimodal" refers to the proximity of a bridge or roadway to other transportation services. Published prior to the MAP-21 legislation, NCHRP Report 590 does not recommend performance criterion related to freight movement and military, although measures suggested for vulnerability criteria to account for military movement when determining "man-made" vulnerability rating (Patidar et al. 2007).

Some states have been identified that utilize freight mobility and military considerations within their bridge project prioritization strategies. For example, Oregon DOT using the criterion of freight mobility needs, which includes performance measures for load capacity, vertical clearance, and geometric clearance. Metrics such as these provide insight into the ability of a bridge to accommodate heavy loads associated with freight and military vehicles (Oregon DOT, 2015). Similarly, Georgia DOT's bridge project prioritization formula utilizes load posting and functional classification as measures of a bridge's impact on mobility.

SHAs in New York, California, and Oklahoma also include multimodal considerations in their prioritization method for bridges or highway infrastructure. California allocates a total of 20 out of 100 points towards multimodal/proximity performance criterion (Johnson, 2008). New York State DOT also considers multimodal access when initially listing potential bridges for repair or replacement (McDonald, 2014). Oklahoma DOT calls the performance criterion Mobility Choice, Connectivity, and Accessibility, and includes the following performance measures towards this criterion: public transit and passenger rail. This performance criterion is not specific to bridges, but to all highway infrastructure in the state of Oklahoma (Oklahoma DOT, 2015).

NCDOT's Prioritization 5.0 has a performance criterion for freight and includes two performance measures (truck volume – 50% and truck % - 50%) plus a future interstate completion factor. Its purpose is to "account for key indicators of freight movement (NCDOT, 2018)." The future interstate completion factor is computed differently for modernization projects vs. other projects as shown in equations A.27 and A.28. The maximum future interstate completion factor is capped at 25 points.

Future Interstate Completion Factor [Modernization Projects] =
((Project Length / Miles Needed to Complete Future Interstate Corridor between NHS Routes) x 100) / 2

(A.27)

Future Interstate Completion Factor [All Other Projects] =
((Project Length / Miles Needed to Complete Future Interstate Corridor between NHS Routes) x 100)

(A.28)

NCDOT's P5.0 also considers the performance criterion of multimodal mobility under the category of Accessibility/Connectivity. This criterion is utilized in Regional Impact and Division Needs project only (not Statewide Mobility projects). Its purpose is to "improve access to opportunity in rural and less-affluent areas and improve interconnectivity of the transportation network (NCDOT, 2018)." In Prioritization 5.0, Accessibility/Connectivity is addressed with two performance measures:

- a county economic indicator (50%), with points based on economic distress indicators such as property tax base per capita, population growth, median household income, and unemployment rate, and
- improve mobility (50%) if projects upgrade mobility of a roadway (such as by elimination of traffic signals, it will be provided points based upon travel time savings per user.

In some instances, multimodal benefit points can also be awarded to projects based on proximity to rail stations, major transit terminals, commercial service airports, red and blue general aviation airports, major military bases, and ferry terminals (NCDOT, 2018).

The current PRI utilized by NCDOT for bridge project prioritization incorporates several measures which indirectly evaluate a bridge's impact on freight movement (such as load capacity reduction and structural evaluation, included in the Sufficiency Rating, as well as the single vehicle load capacity priority in the Deficiency Points). Military needs are currently addressed in the PRI using the STRAHNET designation.

A.4.8 Functionality

Functionality is defined by the geometric characteristics of a particular bridge. Neither MAP-21 nor Prioritization 5.0 include functional performance criteria. It is also not specifically mentioned in NCHRP Report 590's recommendations. NCHRP Report 590 does include performance measures related to functionality, but they are included under the safety performance criterion (Patidar et al., 2007).

Several states do include criteria or measures associated with functionality in their bridge prioritization methods. Indiana DOT includes metrics associated with functional deficiencies under safety measures (Sinha et al., 2009). Oregon DOT includes similar performance measures that target bridge structural deficiencies under the category "Other Deficiencies." Also included in Oregon DOT's prioritization scheme are functional performance measures (such as bridge load capacity) listed under the performance criterion of freight mobility needs (Oregon DOT 2015). VTrans also utilizes a performance criterion of functionality for bridge prioritization, with this criterion worth 5 points out of 100 total points. Measures of functionality include roadway alignment and structure width, which are compared to the state general standards (VTrans, 2013).

A.4.9 Maintenance

Performance criteria linked to maintenance are not specifically mentioned in MAP-21, the STI legislation, NCDOT P5.0, or in NCHRP Report 590. Similarly, a review of the literature indicated that most states do not mention maintenance needs or actions as a factor influencing bridge project prioritization. However, some states do report use of maintenance as a screening measure for eligibility for project funding. For example, South Dakota DOT is requiring that (starting in 2017), all projects seeking a grant will need to have proof of general maintenance, providing records of all maintenance work performed (SDDOT, 2015).

Tennessee, Colorado, and South Carolina are three states identified that specifically include maintenance in their bridge project prioritization formulas (TDOT, 2017; CDOT 2017; SCDOT, 2013). Tennessee DOT uses a performance-based planning process for determining which transportation projects will get funded. Scoring is based on seven performance criteria, where points are summed to achieve a project score ranging from 0 to 100, with 100 being the most important project. One of the performance criterion listed is system maintenance. If the project has pavement or bridge deficiencies, a value of 100 is assigned, while a score of 0 is assigned for a project without these deficiencies. Points are later normalized with the other seven performance criteria to determine the final score of the project (Selin, 2015).

Colorado includes a sub-criterion of "continued significant long-term maintenance and/or interim repair cost" under the economic factors performance criterion when determining bridge project prioritization. This sub-criterion is worth 2 points or 2% of the overall prioritization score (Harris and Laipply, 2013). South Carolina's bridge prioritization utilizes two categories: 75% weighted on a data collection score, such as structural condition, traffic status, ADT, ADTT, and DT, and 25% weighted on an engineering judgment score, including measures such as; environmental impacts, current and future economic development, new schools, etc. The engineering judgment score includes the district maintenance capabilities, the frequency of repairs, and effectiveness of the repairs. It also requires that the division engineer determines the difference between rehabilitation and replacement options (SCDOT, 2013).

A.5 NCHRP Report 590 Recommended Methodology for Bridge Project Prioritization

Most modern bridge prioritization programs are founded within principles of Performance-Based Resource Allocation (PBRA), which is a decision-making framework that objectively selects actions based on defined agency or policy goals using quantitative measures of performance. In the early 2000's, an NCHRP study was funded, with researchers tasked with identifying best practices for SHAs to enhance their (BMS) to aid with the decision-making process at the project and network level. NCHRP Report 590 provides one of the most comprehensive reviews on decision theory techniques recommended for prioritizing projects within a Bridge Management System using multi-objective and multi-constraint optimization. Within an optimization framework, selection of the optimal combination of bridge projects for any given year is done to maximize the "utility" of the selected projects, under the given budgetary and non-budgetary constraints provided.

In most, if not all, instances, the measure of utility is developed from performance measures, which quantify the impact of the project on such metrics as bridge health, traffic congestion, network vulnerability, safety, and many other indicators that are reflected in the current legislation. In NCHRP Report 590, (and as discussed in previous sections of this literature review) a list of performance criteria were compiled that are suggested for use in the evaluation alternative bridge actions and project prioritization (Patidar et al., 2007):

- *Preservation of bridge condition: which would use the National Bridge Inventory, a health index, and the sufficiency rating.*
- *Traffic safety enhancement*
- *Protection from extreme events*
- *Agency cost minimization*
- *User cost minimization*

However, the construction of the utility function should not be performed simply as the sum of individual performance measures, since this fails to capture relative importance and risk. Instead, utility of a bridge replacement, rehabilitation, or preservation project reflects the priority associated with the project by aggregating "value functions" that scale performance measures based on decision maker preferences and also incorporating weighting factors and functions that express decision maker attitudes on importance and risk aversion. In both cases, since the value functions reflect decision maker preferences and the utility functions reflect the decision maker outlook on importance and risk, these functions are best obtained through statistical regression of preference surveys to illicit these preference structures from the decision makers. This framework is shown in Figure A.9.

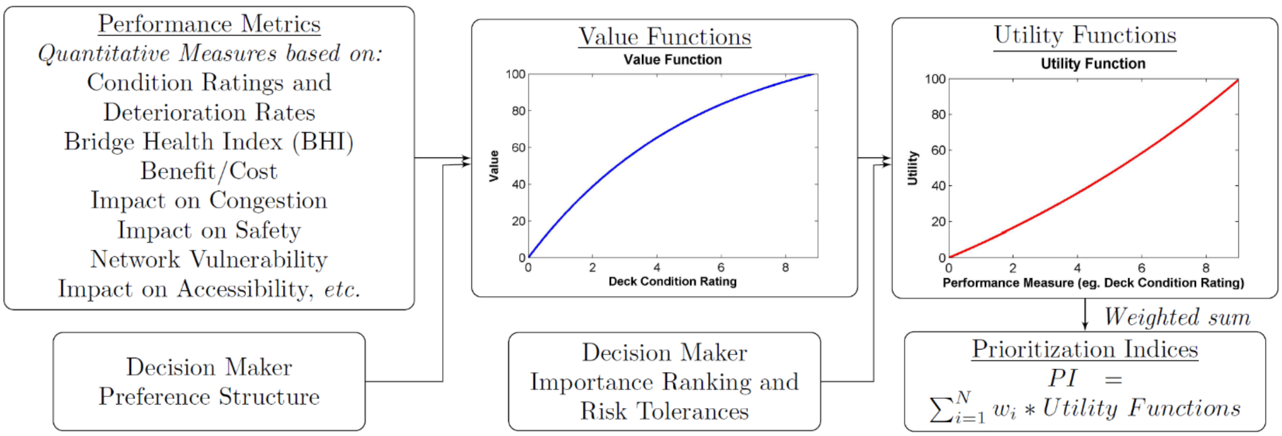


Figure A.9. General NCHRP Recommended Decision Theory Framework for Development of Prioritization Indices from Performance Measures

A.5.1 Survey Techniques to Establish Relative Weighting of Performance Criteria

To move towards current legislative goals while balancing agency preferences and risk tolerances, the relative weight of performance criteria and measures must be specified. This can be done through the use of surveys and decision making techniques that help decision makers determine what is more or less important. Three steps are required to utilize any decision-making technique (Parlos, 2000):

1) Determine the relevant criteria and alternatives.
2) Attach numerical measures to the relative importance of the criteria and to the impacts of the alternatives on those criteria.
3) Process the numerical values to determine a ranking of each alternative.

There are many methods for developing relative weights for each performance measure, including direct weighting, analytical hierarchy process (AHP), observed-derived weighting, and the gamble method (Patidar et al. 2007; Parlos, 2000). In the following sections of this literature review, each of these is briefly introduced and described.

A.5.1.1 Direct Weighting

Direct weighting uses regression analysis to determine the weights applied to multiple performance criteria or performance measures when aggregating value or utility functions into a single index. This method can include point allocation (where survey takers are assigned a total number of points to be distributed amongst each criterion), categorization (where the survey respondent assigns performance measures to different categories or performance criteria), and ranking (survey respondent orders performance measures in a decreasing importance) (Sinha et al., 2009).

For the point allocation method, the decision makers are often allocated 100 points to divide among the given criteria. The NCHRP Report 590 suggests this method is the best method suited for a bridge decision making process (Patidar et al,. 2007). This method, although easy to implement, is not as rigorous as other techniques and may not adequately capture the preferences of the decision maker as effectively (Sinha et al. 2009). Nevertheless, this technique has been utilized by a number of agencies, such as New Jersey, Ohio, and South Dakota, to develop weighting for prioritization strategies used in their BMS (Bacheson et al. 2014; Ohio DOT, 2003, SDDOT, 2016).

A.5.1.2 Analytical Hierarchy Process (AHP)

The analytical hierarchy process (AHP) is a fairly easily implemented methodology for complex decision making, developed by T.L. Saaty. A decision can only be made when the problem, purpose, criteria, and stakeholders are known. AHP achieves the goal of comprehensive decision making by "decomposing the problem into a hierarchy of sub-problems which can more easily be comprehended and subjectively evaluated" (Bhushan and Rai, 2004).

The fundamental framework of the AHP is organized into four main steps (Saaty, 2008):

1) Define the problem / knowledge sought.
2) Structure the decision hierarchy with the ultimate goal on top, then objectives, and all intermediate to lower levels (Figure A.10).
3) Construct pairwise comparisons matrices.
4) Use the priorities obtained from the comparison to weigh the priorities in the level immediately below. Add all the weight values together to obtain the overall priority.

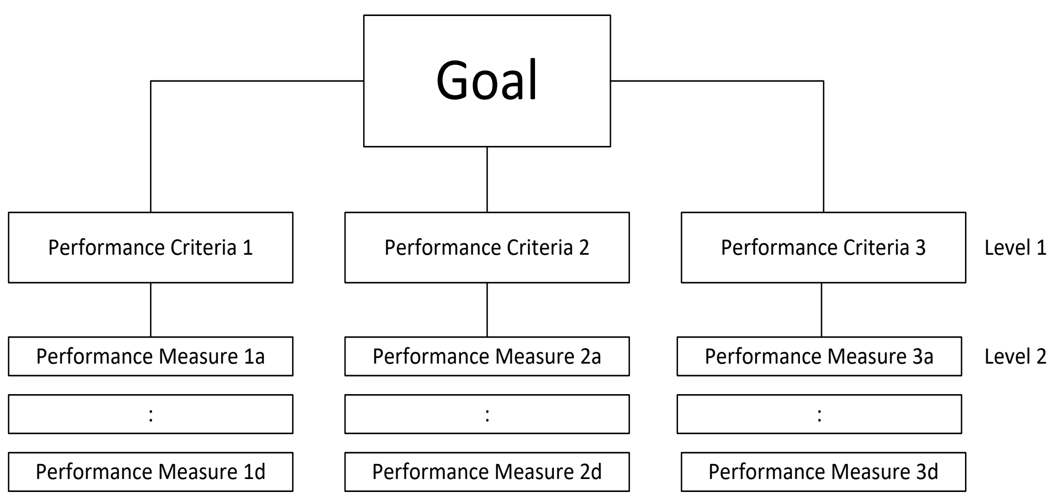


Figure A.10: Generic hierarchic structure (Saaty, 2008)

Determination of the desired priorities for each performance criterion and performance measure is achieved by requiring decision makers to fill out a set of tables. A table is created for each level of hierarchy. For example, a table would be created to compare all the Level 1 Performance Criteria (Saaty, 2008). If *z(i), i* = 1,2,….*n* are the set of given criteria, then *z(i), z(j)* are a pair of criteria on the following comparison matrix (Patidar, et al. 2007):

$$A = \begin{pmatrix} 1 & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ 1/a_{1n} & \cdots & 1 \end{pmatrix} \tag{A.29}$$

where: *A* = comparison matrix

Then the weights would be defined by the following, allowing for deviations (Patidar, et al. 2007):

$$w_i = \frac{1}{n}\sum_{j=1}^{n} a_{ij}w_j \text{ (for } i = 1,2,\ldots.n) \tag{A.30}$$

where: *w = weight*

An overall pairwise comparison is developed using the alternatives. In order to make qualitative judgments between each criterion, a scale is defined. The degree of importance scale first created by Saaty in 1980 uses the integers 1 through 9, as shown in Table 2.3. It is based upon the psychological theory that people cannot make a choice using an infinite set of numbers and also that they cannot distinguish between very small decimal changes such as the change between 3.00 and 3.02 (Parlos, 2000).

Table A.24: Degree of importance scale (Saaty, 2008)

Intensity of Importance	**Definition**
1	Equal Importance
2	Weak
3	Moderate Importance
4	Moderate Plus
5	Strong Importance
6	Strong Plus
7	Very Strong or Demonstrated Importance
8	Very, very strong
9	Extreme Importance

Most researchers and practitioners utilizing AHP continue to use this scale, or slight variations thereof. For example, in bridge prioritization work for the state of Wyoming, Johnson and Ozbek (2013) used the degree of importance scale presented in Table A.25. Another variation appears in the NCHRP Report 590, shown in Table A.26, which only includes numbers 1, 3, 5, 7, and 9 (Patidar et al., 2007). It has been noted that the scale can be varied as long as it is processed the same way by each decision maker surveyed to determine the degree of importance through a pairwise comparison to determine the relative weight for each criterion (Parlos, 2000).

Table A.25: Alternative degree of importance scale used by Johnson and Ozbek, 2013

Intensity of Importance	Definition
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Absolute Importance
2,4,6,8	Intermediate values

Table A.26: Alternative degree of importance scale used in NCHRP 590 (from Patidar et al., 2007)

If:	Then ratio of X/Y should be:
Criterion X is extremely more important than Criterion Y	9
Criterion X is strongly more important than Criterion Y	7
Criterion X is moderately more important than Criterion Y	5
Criterion X is slightly more important than Criterion Y	3
Criterion X is equally more important than Criterion Y	1
Criterion X is slightly less important than Criterion Y	1/3
Criterion X is moderately less important than Criterion Y	1/5
Criterion X is strongly less important than Criterion Y	1/7
Criterion X is extremely less important than Criterion Y	1/9

To reduce the confusion that may occur when respondents are requested to fill out a survey that presents a traditional pairwise comparison, researchers Johnson and Ozbek (2013) developed a pairwise comparison spreadsheet that follows the AHP methodology. It is organized by having only two items compared to one another at the time and the participant must first choose which one is more important and then reactive degree of importance using the previously mentioned importance scale (Table A.27). Essentially, this approach breaks down the AHP matrix into pairwise comparisons representing each cell in the matrix, with pairings compared in the both orders (twice in each survey) to facilitate a consistency check.

Table A.27: Spreadsheet application (Johnson and Ozbek, 2013)

Item A	Item B	More Important	Degree of Importance
Deck / Slab	Protective System		
Deck / Slab	Approach Slabs		
Deck / Slab	Bridge Railing		
Deck / Slab	Joints		
Deck / Slab	Superstructure		
Deck / Slab	Bearings		
Deck / Slab	Substructure		
Deck / Slab	Inventory Rating		
Deck / Slab	Posting		

The survey respondents will each complete the pairwise comparison by assigning preference and the degree of importance. For each pair once finished, the answers need to be checked to ensure that the respondent was consistent with his or her answers. This is done by using the consistency ratio formula which uses a linear algebraic method to normalize principal eigenvectors to represent each of the weights (Saaty, 2008). The consistency ratio (CR) formula is determined by first finding the consistency index (CI), which is calculated as:

$$CI = (\lambda_{max} - n) / (n - 1)$$
(A.31)

where: CI = consistency index
λ_{max} = the maximum eigenvalue of the comparison matrix, A
n = the number of criteria

The CI is then compared with the random consistency index (RI) (Table A.28) to determine the consistency ratio.

$$CR = CI / RI$$
(A.32)

where: CR = consistency ratio
CI = consistency index, and
RI = random consistency index (from Table 2.7).

A participant is considered consistent if they obtain a CR of 0.10 or less where eigenvalue corresponds to the principal eigenvector (Johnson and Ozbek, 2013).

Table A.28: Random consistency index (RI) (from Teknomo, 2006)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Once all the surveys are completed, the results are combined by finding the geometric mean of each individual performance measure and performance criteria. From this process, a combined pairwise comparison is calculated to determine the final weights between each component that reflects the overall judgement of the group (Johnson and Ozbek, 2013). For example, the average of the group's answers would be arranged in a pairwise comparison matrix, as seen in Table A.29. The weights are derived by taking the total of the row divided by the sum of each of the rows in the table (Saaty, 2008).

Table A.29 Pairwise comparison matrix (from Saaty, 2008)

Drink Consumption in US	Coffee	Wine	Tea	Beer	Sodas	Milk	Water	Sum	Weighted Total
Coffee	1	9	5	2	1	1	1/2	19.50	0.185
Wine	1/9	1	1/3	1/9	1/9	1/9	1/9	1.89	0.018
Tea	1/5	2	1	1/3	1/4	1/3	1/9	4.23	0.040
Beer	1/2	9	3	1	1/2	1	1/3	15.33	0.146
Sodas	1	9	4	2	1	2	1/2	19.50	0.185
Milk	1	9	3	1	1/2	1	1/3	15.83	0.150
Water	2	9	9	3	2	3	1	29.00	0.275
								105.28	1

AHP has been utilized to assist in making decisions in wide variety of areas. For example, it has been used in the economic/management areas for auditing, database selection, design, and architecture. It has also been used in politics for arms control, conflicts and negotiations, political candidacy, and security assessments (Saaty and Vargas, 2012). In engineering applications, AHP has been utilized in road infrastructure management in Ontario to allocate funding. This study resulted in use of the following performance measures: Pavement Condition Index (PCI), Pavement Priority Number (PPN), Road Type (Road), Pavement Roughness (IRI), Structure Number (SN_{eff}), and Pavement Friction (SN_{40}) (Smith, 2012).

A specific example of the AHP method being used for bridge applications in the US can be found in a study conducted by Johnson and Ozbek (2013) for the Colorado DOT. They used AHP to determine the relative importance of the following bridge attributes: 1) Structural Condition, 2) Impact on Public, and 3) Hazard Resistance. They conducted a two-part study, the first part used a survey questionnaire to identify the bridge management component items and the second part determined the relative importance of the items to develop the weighting factors by AHP (Johnson and Ozbek, 2013).

A.5.1.3 Delphi Technique

Committees are often organized to make decisions on a particular subject or situation, including prioritization of bridge projects. When such panels are organized, there exists the possibility that one person (or group of people) is more dominant and vocal than others, therefore potentially affecting the overall majority opinion. To mitigate this problem, the Delphi technique can be incorporated into the surveying and decision making process (Saito and Sinha, 1991). The Delphi technique consists of three major features: anonymity, iterations with controlled feedback, and statistical analysis of responses (Dickey and Watts, 1978). A first survey is completed individually by each member on the panel. After each survey, controlled feedback is presented to the panel, this allows the panel to only know the collective thoughts of the group. This method allows the answers of the participants to be anonymous to one another, which allows for them to freely reconsider their previous answers without having to admit they were wrong (Saito and Sinha, 1991).

This Delphi technique was used by researchers Saito and Sinha (1991) for the Indiana DOT to prepare inspection guidelines for bridge condition ratings, where two rounds of surveys were implemented. After the second round, the variations in responses among the panel decreased for most questions. The researchers found that using this method was successful in helping the inspectors make adjustments and second thoughts to their first attempt on the survey (Saito and Sinha, 1991).

A.5.2 Value and Utility Functions

Decision-making frameworks often rely on the use of value and utility functions to facilitate optimization of decision involving combinations of options. The measure of utility is developed from performance measures, which quantify the impact of a project on meeting desired goals or criteria. Value functions are used to scale performance measures based on decision making preference structure. Utility functions incorporate decision maker importance and risk tolerances. Combined, these two functions can objectively select actions based upon defined agency goals using quantitative measures of performance (Patidar et al., 2007). NCHRP Report 590 recommends this approach for prioritizing projects within a BMS, and in this section, a brief background on value and utility functions is presented.

Utility theory assumes that decision makers are able to choose among all possible alternatives available, and their choice provides the most satisfaction amongst the options (Patidar et al., 2007). A value function is a scalar index that represents the preference of the available alternative, and is therefore a mathematical representation of a decision maker's preference structure. Value functions assume that the decision maker can analyze all the alternatives available, allowing decision makers to be content with their choice. Therefore, the value function assumes that all potential information that influences a criterion can be captured in a value function. Generally, value functions are used in scenarios where the consequence of each alternative is known with certainty. Therefore, the main consequence of using value functions to inform decisions with multiple performance goals is that the use of multi-criteria value functions does not incorporate risk associated with tradeoffs (Patidar et al. 2007). An example of a value function using Bridge Health Index is shown in Figure A.11.

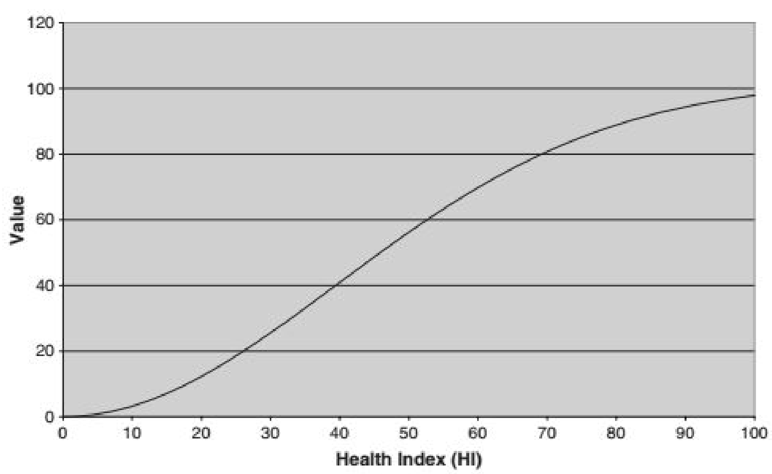


Figure A.11: Example value function (from Patidar el al. 2007)

To analyze a decision for a multi-criteria problem, the decision maker's multivariate value function needs to be assessed (Patidar el al. 2007):

$$v\ (z) = v\ (\ z_1,\ z_2,\ \ldots\ldots\ ,\ z_n) \tag{A.33}$$

where: v = value function

z = the consequence set of an alternative in terms of n criteria: $z_1, z_2, \ldots, z_p$

If two alternatives exist (alternative A and alternative B), each defined by a set of measures $\{z\}$, function A.34 below, can be used to address the trade-offs among multiple criteria, or sets of measures:

$$v(\{z\}^A) > v(\{z\}^B) \tag{A.34}$$

If option A is preferred to option B. Patidar et al. (2007) indicate that an example multivariate value function used in a bridge management setting would be a function in three-dimensional space that provides a scalar value to each possible combination of health index and geometric health rating.

It can be difficult to define the multivariate value function because of the multi-dimensionality associated with the problem. To negotiate this, issue the multi-variate function is typically reduced (or decomposed) to a single-criterion value function. When the criterion are mutually preferentially independent, the single-criterion value functions can be combined into the following additive value function (Keeney and Raiffa, 1976):

$$v\ (z_1,\ z_2,\ \ldots\ldots,\ z_p) = \sum_{i=1}^{n} v_1(z_i) \tag{A.35}$$

where: v_1 = single criterion value function over the criterion z_i.

A utility function, unlike a value function, includes the decision maker's preference regarding a select attribute with the inclusion of risk preferences (Patidar et al. 2007). The utility function's expected values are used to evaluate alternatives, where the alternative with the maximum expected utility is preferred. It consists of two important properties: 1) the utility of any criterion is the expected utility of its result, 2) if one criterion is preferred over another, then it will have a higher utility (Howard, 1968). The utility theory states the following: given the criteria $z_1, z_2, \ldots. z_n,$ if the criteria are mutually utility independent, then the following multiplicative utility function exist:

$$Ku(z_1,\ z_2, \ldots.. z_p) + 1 = \prod_{i=1}^{n}[\ kk_i u_i(z_i) + 1] \tag{A.36}$$

where: u_i = single criterion utility function over the criterion z_i
$k \; and \; k_i$= scaling constants

Combining different performance measures presents challenges, since the levels of each measure do not have a common scale. For example, NBI infrastructure condition ratings have an integer scale from 0 to 9, while the Health Index is on a 0 to 100 scale. Furthermore, the relative contributions, or weighting, of the individual performance measures to the combined index needs to reflect both preference and risk. The NCHRP 590 Report used utility theory in order to convert all performance measures to a common scale in a way that can be clearly understood and changed in the future as the needs of the bridge agency change. Utility theory provides a method of capturing and representing the preferences of decision makers in terms of trade-offs and how those preferences are affected by risk attitudes (Patidar et al., 2007). The effects of bridge improvement project candidates on the criteria are calculated with a utility function, which is a mathematical representation of the preference structure.

The process that was used to develop utility functions in the NCHRP 590 Report consisted of three main steps: weighting, scaling, and amalgamation. The weighting step consists of developing relative weights for the criteria and performance measures by using the results of a practitioner survey. The scaling step involved the development of single-criterion utility functions that represent the practitioner preference structure for individual performance measures. The final step, amalgamation, is the combination of the single-criterion utility functions into a single utility function that provides a single prioritization score for a bridge improvement project.

The five criteria and 12 performance measures that are considered in the NCHRP 590 illustrative decision model are summarized in Table A.30. Each of the criteria are associated with a set of performance measures to provide a way of quantifying how each bridge project candidate contributes to the criteria. For example, there are three performance measures that are associated with the Preservation of Bridge Condition criterion, which are NBI Ratings, Health Index, and Sufficiency Rating. Each of the performance measures have different levels of importance to the decision maker and are assigned corresponding values, called relative weights, to quantify the importance preference of the decision maker. The Health Index with a value of 0.507 will have a larger impact for the Preservation of Bridge Condition criteria than either the sufficiency rating (0.222) or NBI ratings (0.271). Likewise, each of the individual criterion are assigned relative weight values to reflect their contribution to the overall index. For example, the Preservation of Bridge Condition criterion with a relative weight of 0.360 will impact the overall value of a bridge improvement project more significantly than User Cost Minimization with a weight of 0.110. These relative weights were determined using practitioner surveys.

Table A.30: Criteria, Performance Measures, and Relative Weights Developed for the NCHRP Report 590 BMS Framework.

Criteria	**Performance Measures**
Preservation of Bridge Condition (0.360)	NBI Ratings (0.271)
	Health Index (0.507)
	Sufficiency Rating (0.222)

Traffic Safety Enhancement (0.205)	Geometric Rating (0.570)
	Inventory Rating (0.430)
Protection from Extreme Events (0.150)	Scour Vulnerability Rating (0.385)
	Fatigue/Fracture Criticality Rating (0.265)
	Earthquake Vulnerability Rating (0.205)
	Other Disaster Vulnerability Rating (0.145)
Agency Cost Minimization (0.175)	Initial Cost (N/A)
	Life-Cycle Agency Cost (N/A)
User Cost Minimization (0.110)	Life-Cycle User Cost (1)

The development of single-criterion utility functions in the scaling step first involves the creation of single-criterion value functions. A single-criterion value function provides a real number scalar representation of preference, known as value, of a decision maker for all levels of the criterion (Patidar et al., 2007). A single-criterion value function was developed for each performance measure, with the exception of the cost related measures, such as life-cycle agency cost. For initial costs, life-cycle agency cost, and life-cycle user costs, a net present value analysis was performed. An example of a value function is shown in Figure A.12, where the value to the bridge manager is shown for any level of the deck condition rating performance measure.

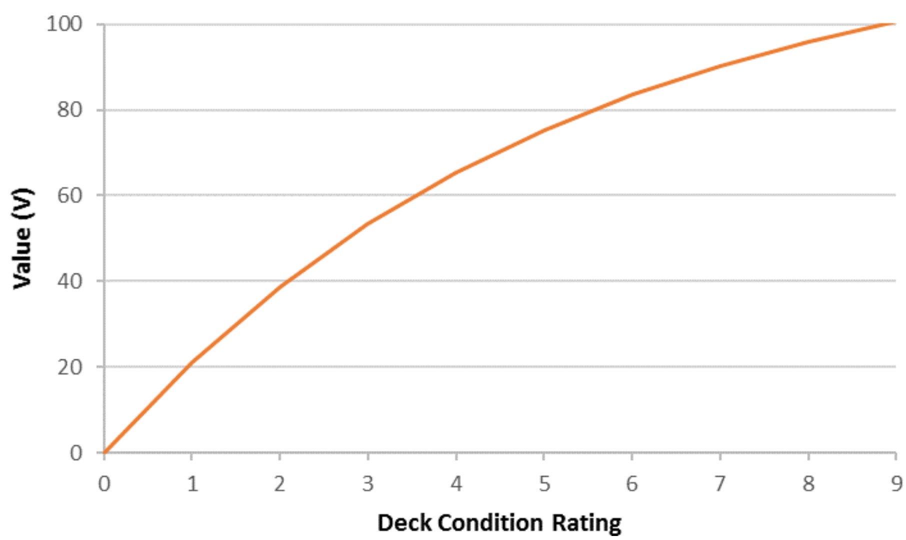


Figure A.12: Example of a Single-Criteria Value Function, adapted from Patidar, 2007.

A single-criterion utility function takes the value function and adjusts the form based on the risk preferences of the decision maker. In utility theory, when the stakes are increased, the value of an alternative changes accordingly (Skinner, 2009). For a risk averse or conservative decision maker, the value of a very risky alternative will be reduced. Utility theory allows an estimation of the value affected by risk, or utility, using a method called certain equivalence. Certain equivalence is a measure of value that a decision maker would place on the certainty of a potential outcome. The value difference between the expected value and the certain equivalence is known as the risk premium and is shown in Figure A.13.

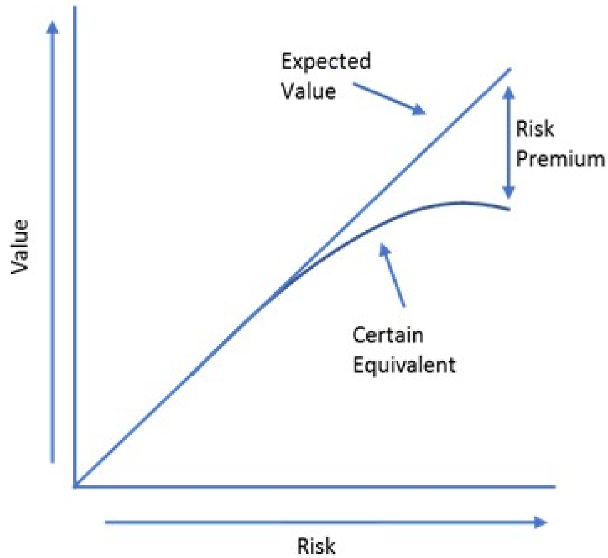


Figure A.13: Relationship Between Certain Equivalent and Expected Value, adapted from Skinner, 2009.

In the NCHRP 590 Report, three types of risk attitudes were assessed for each of the performance measures: risk seeking, risk neutral, and risk averse. These risk attitudes can be modeled, respectively, by

$$u(z) \sim -e^{-cv(z)},\ c > 0 \tag{A.37}$$

$$u(z) \sim v(z) \tag{A.38}$$

$$u(z) \sim e^{cv(z)},\ c > 0 \tag{A.39}$$

where $u(z)$ is a single-criterion utility function, $v(z)$ is a single-criterion value function, z represents the level of a given performance measure, and c is a constant used to model the effect of risk on the utility. The effects of the different types of risk attitudes on the value of the decision are depicted in Figure A.14. In the NCHRP 590 study, the type of risk for each performance measure was determined using the average of certainty equivalents from the gamble method portion of the practitioner surveys. Similar to the individual value functions, the single-criterion utility function is scaled from a range of lowest utility (0) to highest utility (100).

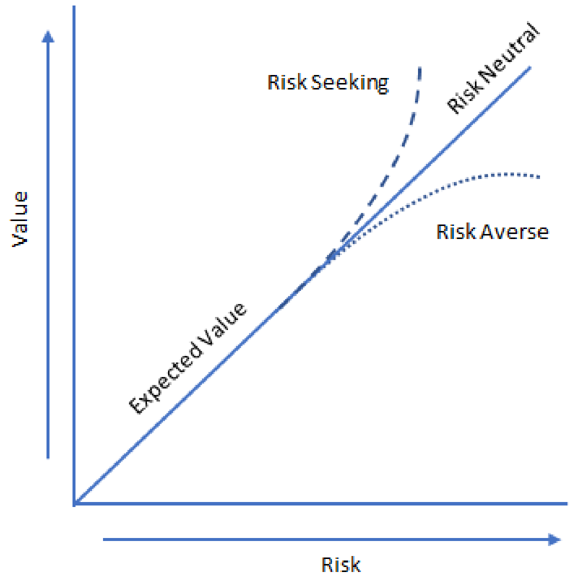


Figure A.14: Effects of Risk on Value Based on Risk Attitudes, adapted from Skinner, 2009.

As an example, the single-criterion utility function and corresponding single-criterion value function for deck condition rating are shown in Figure A.15. This performance measure was found to have an average certainty equivalent that correlated with the risk averse form, which is evident in the figure as all utility values are lower than the expected values. In the NCHRP Report 590, the risk averse form of single-criterion utility functions was simplified as a linear function. The remainder of single-criterion utility functions were found to be risk neutral and thus modeled the same as the single-criterion value function.

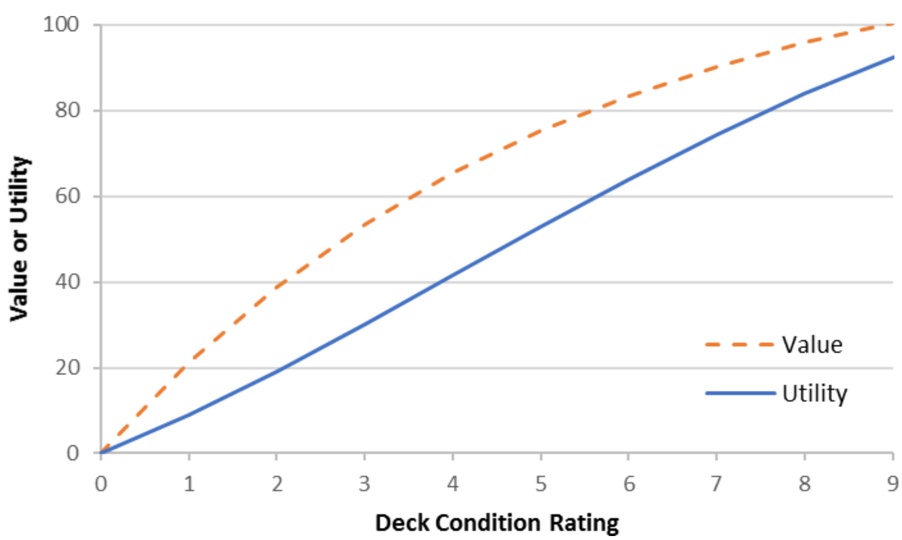


Figure A.15: Example of a Single-Criterion Value and Utility Function, adapted from Patidar et al., 2007.

The final step, amalgamation involves the combination of the single criterion utility functions into a single, multi-criteria utility function. Scaling constants, which were derived from the practitioner survey, were used to determine the functional form used to create the utility function. Most commonly, multi-criteria utility functions are developed using either a multiplicative form:

$$ku(z_1, z_2, \ldots\ldots, z_p) + 1 = \prod_{i=1}^{p}[kk_i u(z_i) + 1] \quad \text{(A.40)}$$

or an additive form of

$$u(z_1, z_2 \ldots\ldots) = \sum_{p}^{i=1} k_1 u_i(z_i) \quad \text{(A.41)}$$

where k, k_i are relative weighting scaling constants and $u_i(z_i)$ is a single criterion utility function. NCHRP 590 used the multiplicative utility form to develop their multi-criteria utility functions. Since the multi-criteria utility function aggregates all of the performance measures and criteria into a single score, it can represent the importance of a bridge improvement action based on the performance measures. With such an approach, projects can be directly compared under the assumption that if

$$u(z^{l}) > u(z^{ll}) \quad \text{(A.42)}$$

the bridge improvement candidate with the set of performance measures z^{l} is prefer- able to another bridge improvement candidate with the set of performance measures z^{ll}.

A.5.2.1 Mid-Value Splitting Technique

One technique for developing a value function is the mid-value splitting technique. The mid-value splitting technique uses information from survey responses to isolate information regarding their "indifferences" towards changes in the performance measure levels (Sinha and Labi, 2007). In bridge management, this technique is particularly useful in quantifying stakeholder preferences for changes in condition ratings, such as improvements (associated with maintenance actions) or decreases (associated with deterioration) (Patidar et al., 2007). Using the mid-value splitting technique, there is a four step process to determine the decision maker's view on a changing criteria value. The following example uses deck condition (DC), which is based on a 0 to 9 scale, where v (DC = 0) = 0 and v (DC = 9) = 100:

1) Find X_{50} where v (DC = X_{50}) = 50. To find X_{50}, determine where the decision maker is equally delighted with:
   - An improvement in deck condition from 0 to X_{50}
   - An improvement in deck condition from X_{50} to 9

Example: $X_{50} = 4$

2) Find X_{25} where v (DC = X_{25}) = 25. To find X_{25}, determine where the decision maker is equally delighted with:
   - An improvement in deck condition from 0 to X_{25}
   - An improvement in deck condition from X_{25} to X_{50}

   Example: $X_{25} = 2$

3) Find X_{75} where v(DC = X_{75}) = 75. To find X_{75}, determine where the decision maker is equally delighted with:
   - An improvement in deck condition from X_{50} to X_{75}

     As an improvement in deck condition from X_{75} to 9

   Example: $X_{50} = 7$

4) Consistency Check. Is the decision maker equally satisfied with
   - An improvement in deck condition from DC = X_{25} to DC = X_{50}
   - An improvement in deck condition from DC = X_{50} to DC = X_{75}

If the respondent is satisfied, then the values are considered consistent. If not, the decision maker must adjust their responses to the question posed in steps 1 through 3 until they are satisfied (Patidar et al., 2007). Once all respondents have answered the mid-value splitting questions, the answers can be averaged or otherwise aggregated to provide a single value function representing the group's preferences.

<u>A.5.2.2 Approaches Utilized by Other States</u>

A.5.2.2.1 Indiana

The Indiana Bridge Management System (IBMS) prioritizes bridge improvement actions using disutility change [Sinha et al., 2009]. Disutility represents the level of undesirability of the condition of a bridge based on the preferences of the bridge manager. A disutility function is the inverse of a utility function, where criteria with poorer levels are given a higher value. This results in bridges with the most need for improvement having the highest value. An important distinction in the approach used in this study relative to the NCHRP Report 590 is that the disutility change used to develop the ranking value, is the difference in disutility value of the bridge with improvement and without improvement. The disutility change is based on "delta values" calculated in the Decision Tree (DTREE) module of the IBMS. Delta values are the projected increase of condition ratings and other performance measures expected to be caused by an improvement action. The performance measures, criteria and relative weights for this study were based on previous survey results obtained from an expert panel of bridge managers [Saito and Sinha, 1989] and are summarized in Table A.31.

Table A.31: Criteria, Performance Measures, and Relative Weights Developed for the IBMS Ranking Module (Adapted from Sinha et al., 2009.)

Criteria	Performance Measures
Economic Efficiency (10 Points)	Agency Cost (50%)
	User Cost (50%)
Bridge Condition Preservation (50 Points)	Structure Condition (40%)
	Remaining Service Life (40%)
	Wearing Surface (20%)
Bridge Safety Disutility (30 Points)	Clear Deck Width (30%)
	Vertical Clearance Over (10%)
	Horizontal Clearance Under (10%)
	Vertical Clearance Under (10%)
	Inventory Rating (40%)
Community Impact Disutility (10 Points)	Detour Length (100%)

The intent of the prioritization process was to improve economic efficiency, preserve bridge condition states, improve bridge traffic safety, and reduce community impact. The measure of economic efficiency was based on bridge life-cycle agency and user costs, which are calculated in the Life Cycle Cost (LCCOST) module of the IBMS. Preservation of bridge condition refers to maintaining the structural integrity and physical condition of a bridge and was measured by the minimum structure condition rating, remaining service life, and wearing surface. Bridge traffic safety describes the spatial adequacy and geometric design of a bridge and was based on the ratio of current levels to desirable levels for clear deck width, vertical clearance over, vertical clearance under, and horizontal clearance. The desirability levels for each measure are calculated in the DTREE module. The community impact criterion reflects them safety risk to commuters that use the bridge as well as the increase in delivery costs for nearby businesses and is measured by detour length. Specifically, the detour disutility function for the With Improvement scenario is calculated with

$$U_{DLB} = 100 - \frac{100*(g-DL)^n}{g_1} \quad \text{(A.43)}$$

where U_{DLB} is the disutility value without improvement; g_1 is the minimum detour length required for a disutility of 100; DL is the detour length, and n is a constant. The detour utility for the Without Improvement scenario is

$$U_{DLA} = \frac{(dl-dy)*U_{DLB}}{dl} \quad \text{(A.44)}$$

where U_{DLA} is disutility value with improvement, dl is the design life of the bridge, and dy is the number of years until replacement.

The disutility functions developed for each of the performance measures are reproduced in Figure A.16. There are three main forms that the disutility functions take: linear, concave, and convex. These variations of the functional shape allow the model to reflect the risk attitudes of the panel of bridge experts (risk seeking, risk neutral, or risk averse). These standard shapes of disutility functions are shown in Figure A.17. The inflection point at value 2 is the break point where disutility of a bridge is reduced and the second inflection point at 9 is the break point where the bridge is in perfect condition.

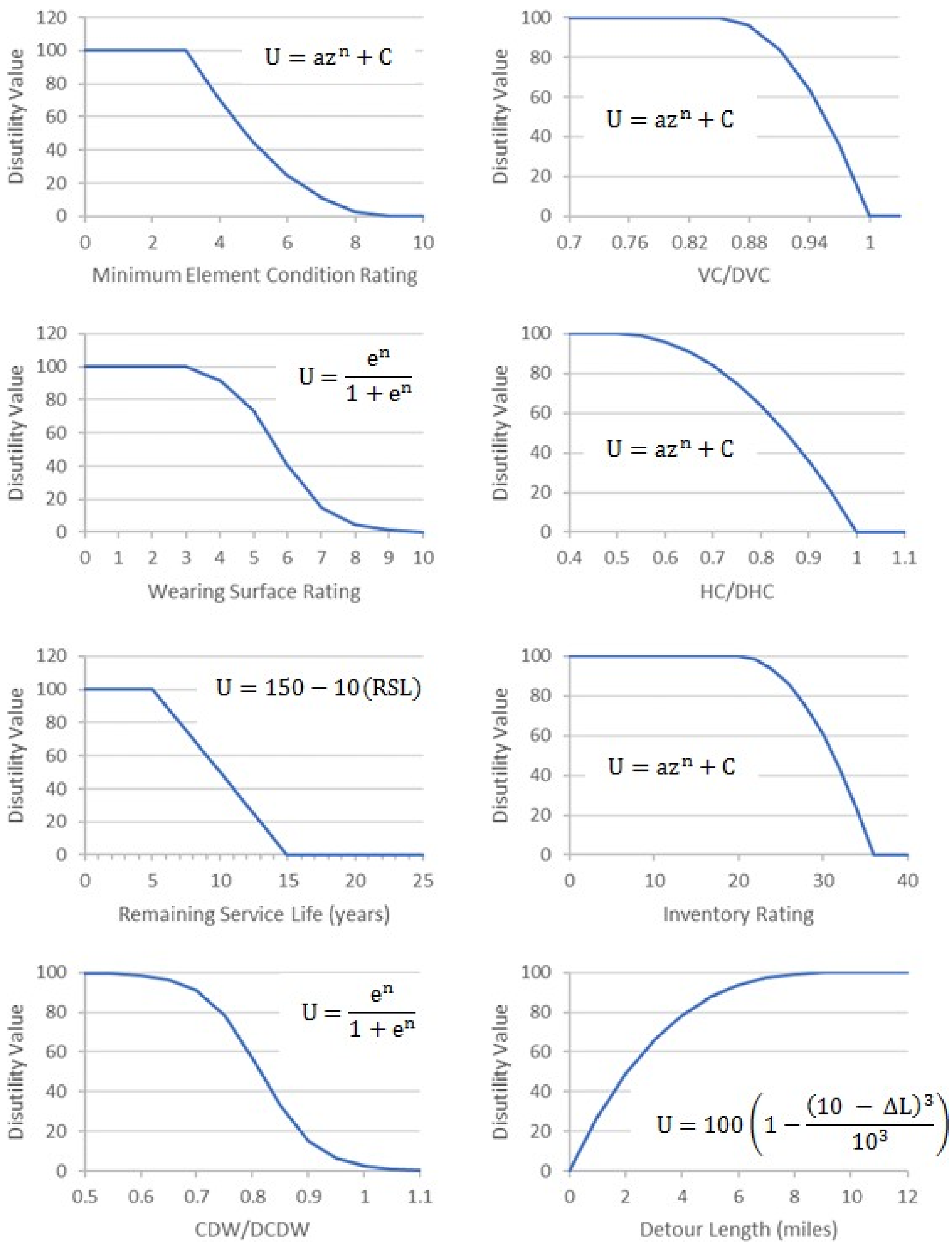


Figure A.16: IBMS Performance Measure Disutility Functions, adapted from Sinha et al., 2009.

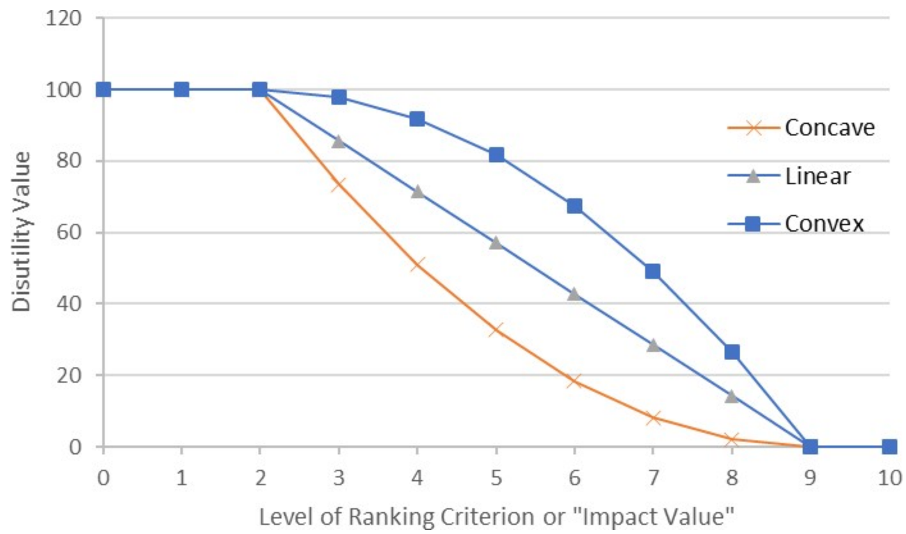


Figure A.17: IBMS Disutility Standard Shapes, adapted from Sinha et al., 2009

The disutility for an individual criterion, U_z, was calculated from the disutility functions of associated performance measures with the following equation

$$U = \sum_{p^*}^{z=1} W_i U_i \tag{A.45}$$

where U_i is the disutility for an individual performance measure i and p is the number of performance measures associated with the criterion. Additionally, the composite disutility function U has the same additive functional form

$$U = \sum_{p^*}^{z=1} W_z U_z \tag{A.46}$$

where p^* is the number of performance criteria.

A.5.2.2.2 California

The California Department of Transportation (Caltrans) combines benefit-cost ratios and utility functions to prioritize preservation projects among the 13,000 bridges in the California transportation system (Johnson, 2008). One of the main benefits of using utility functions noted by the author is that it allows a clear way of combining criteria with different scales since the utility for each criteria are evaluated on a common scale from 0 to 1. Additionally, utility functions allow risk-associated criteria that were not previously included in previous project prioritization, such as scour potential and seismic risk, to be included. In this study, the utility benefit-cost ratio was calculated as

$$\text{Project Utility B/C Ratio} = U_t(TEV)/\text{Project Cost} \tag{A.47}$$

where U_t is the net project utility and *TEV* is the total element value of a bridge. The *TEV* is a quantitative method to describe the value of the bridge structure and allows the utility to be scaled by the size a bridge (Shepard and Johnson, 2001).

The utility functions developed in this study were based on five criteria: rehabilitation and replacement needs, scour needs, bridge rail upgrade needs, seismic retrofit needs, and mobility needs. The associated measures and relative weights for these measures that were developed in the study are shown in Table A.32. In contrast to the prior studies, the performance measures do not have explicit relative weights. Instead, the utility functions were developed only for the criteria and not for each individual performance measure.

Table A.32: Goals and Performance Measures Developed for the NCHRP Report 590 BMS Framework

Utility Component	**Key Parameters**
Rehabilitation and Replacement Needs (25 Points)	BHI, ADT, Repair Urgency (U), and DL
Scour (20 Points)	NBI SC, ADT, and DL
Bridge Rail Upgrade Needs (10 Points)	Caltrans seismic priority (S_v) ADT, and DL
Seismic Retrofit Needs (25 Points)	Caltrans rail upgrade score (RS)
Mobility Needs (20 Points)	Pontis improvement benefit (P)

The utility function for each of the criterion were developed with the logit form

$$X_i = \frac{1}{1+e^{-C_i}} \quad \text{(A.48)}$$

where X_i is the utility function for each criteria and C_i is a function of the significant decision parameters for each component. The *C* functions were calculated in a pre- vious iteration of the Caltrans BMS to calculate the value of each criteria. The net utility, or multi-criteria utility function, for a project is calculated using the additive functional form

$$U_t = \sum \alpha_i \beta_i X_i \quad \text{(A.49)}$$

where U_t is the utility, X_i is the i^{th} single-criterion utility function, α_i is a binary variable indicating whether representing the single-criterion utility function applied to a given structure, and β_i is the relative weight of a given single-criterion utility function.

A.5.2.2.3 Virginia

The Virginia DOT (VDOT) ranks all state-maintained transportation structures by transportation network importance using a cumulative score called the Importance Factor (IF) score in order to assist in the decision process of determining structure should have priority for maintenance, replacement, and rehabilitation expenditures (Moruza et al., 2016). The IF score consists of nine explanatory variables, five of which are modeled using index value functions and the remaining four are binary variables that indicate if a structure is part of a defined highway system. These explanatory variables in the IF score are shown in Table A.33. The relative weights for each of the explanatory variables were determined using input from both the expert panel opinions as well as regression analysis. A process called backcalculated nonstandardized normalized coefficients (BNN) was applied to create the final relative weights in a manner that utilized both the results from the practitioner surveys and the statistical regression. An additive form of the multi-criteria utility function was used to combine the explanatory variable values into a single value.

Table A.33: VDOT IF Score Explanatory Variables and Performance Measures

Variable	Name	Associated Performance Measures
A	ADT/LN	ADT, Number of Lanes
B	ADTT/LN	ADTT, Number of Lanes
C	AGR(ADT)	FADT, ADT, YFADT, YADT
D	Bypass Impact	Detour Length, ADT
E	Access Impact	Bypass Impact, POI, PROX
F	Base Highway	BHN
G	Strategic Highways	STRAHNET
H	Surface Transportation	STAA
	Action Agreement	
I	Virginia Highway System	VSYS

Unlike most bridge prioritization formulas, the IF score does not have explanatory variables that use physical condition inventory items, such as geometric ratings or structural condition scores (substructure, superstructure, and deck). Instead, the IF score uses inventory items that measure the current and future use of a structure, bypass impact, access impact, and association with designated highway networks. The current use of a structure is measured by ADT per lane (ADT/LN) and ADTT per lane (ADTT/LN) of the structure. The inclusion of lane data allows a measure of usage relative to the capacity of a structure. The Annualized Growth Rate, $AGR(ADT)$, is a measure of the estimated increase of usage for a structure each year and is calculated with equation A.50.

$$AGR(ADT) = [\frac{FADT}{ADT}]^{1/(YFADT-YADT+1)} - 1 \quad \text{(A.50)}$$

where :$FADT$ = Future Average Daily Traffic
$YADT$ = Year of Average Daily Traffic
$YFADT$ = Year of Future Average Daily Traffic

This formula was used instead of FADT since the base year and future year to calculate

FADT for each structure is not consistent among transportation structures. Bypass Impact is the combined effect of ADT and detour length if a structure was closed. The Access Impact variable represents the importance of a transportation structure based on the number of critical facilities, also referred to as Points of Interest (POI), in close proximity to the transportation structure. Schools, police and fire departments, and hospitals are examples of POIs. Information about critical facility locations were derived from the VDOT Geographic Information System (GIS) department. POIs within a three mile radius of a transportation structure were considered for the Access Impact calculation, where POIs closer to a transportation structure were assigned a higher value. The remainder of explanatory variables are binary indicators that show if a structure is a component of a designated highway network as defined by VDOT. The preference structure for each of the explanatory variables, except for the highway network indicators, are modeled with value functions. In the context of the IF score, the value functions are referred to as index value functions. Each index value function uses raw data from the VDOT bridge inventory, however there were a variety of methods that were implemented to develop the final forms of the index value functions. The index value functions representing the preference structure of *ADT/LN* and *ADTT/LN* were developed using empirical cumulative value functions (ECDF) and simplified using a step function. The index value function for $AGR(ADT)$ was created with an ECDF step function of the values developed with Equation A.50. The Bypass Impact index value function was developed as the sum of the ECDFs for ADT and Bypass Detour Length (BYP). The Access Impact index is calculated using the BYP index value and proximity index value function with the equation

$$E_k = v(BYP) \times v(PROX)] \tag{A.51}$$

where : E_k = Index Value for Access Impact

$v(BYP)$ = Index Value of Bypass Impact

n = Count of key locations

j = Distance interval a key location is in

$v(PROX)$ = Distance from transportation structure to key location

To provide an example of the index value functions, the ADT/LN index value function is shown in Figure 2.11. An index value of 1 was assigned to structures with an ADT/LN of 8500 and higher since these structures represented about 10% of the overall structure population. A similar method was applied for structures with an ADT/LN of 23 or lower. The index value function is not the actual ECDF, but a trendline that approximates the ECDF.

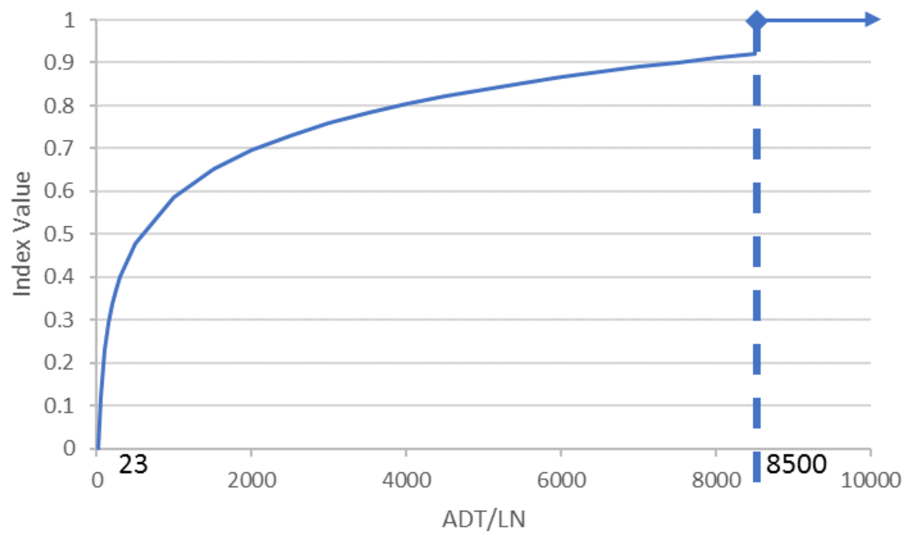


Figure A.18: VDOT Index Value Function for ADT/LN

The relative weights for the explanatory variables were developed using BNN coefficients that reflect the intended and actual impacts of each variable. The intended relative weights were developed by the VDOT expert panel, while the actual relative weights were developed using linear regression analysis. Development of BNN coefficients, which is a method of adjusting actual impacts of a model to better reflect the desired impact, was applied to better align the performance of the model with the intentions of the expert panel using the equation

$$\beta_i^* = \beta_i \times \left(\frac{s_{X_i}}{s_Y}\right) \quad (A.52)$$

where :β_i^* is the standardized coefficient for standardized index values of variable *i*

β_i is the nonstandardized coefficient for nonstandardized index values of variable *i*

X_i is the set of nonstandardized index values for variable *i*

Y is the IF score

S is the standard deviation statistic

The relative weights developed by the expert panel, linear regression, and BNN coefficients are shown in Table A.34.

Table A.34: Relative Weights Developed for VDOT IF Score Based on Different Methods

Variable	Name	Panel	Regression	BNN
A	ADT/LN	0.20	0.345	0.147
B	ADTT/LN	0.10	0.161	0.079
C	AGR(ADT)	0.15	0.199	0.143
D	Bypass Impact	0.25	0.281	0.282

E	Access Impact	0.10	0.054	0.233
F	Base Highway	0.05	0.129	0.024
G	Strategic Highways	0.05	0.099	0.032
H	Surface Transportation Authorization Act Network	0.05	0.108	0.029
I	Virginia Highway System	0.05	0.102	0.031

The IF score of a transportation structure was developed using the additive multi-criteria utility function

$$IF\ Score\ = \sum \beta_i X_i \tag{A.53}$$

where X_i is the i^{th} index value and β_i is the BNN relative weight of a given index value. The calculation of the IF score for each of the VDOT structures was automated by an Excel VBA macro.

A.6 Other Examples of Structural Project Prioritization

Multi-criteria utility theory is implemented in other asset management prioritization practices, with significant prior work related to municipal sewer systems. The rising costs of emergency sewer pipe section repairs associated with the previous practice of random pipe section structural inspections motivated studies aimed at developing probabilistic models to predict if a pipe section is in a deficient state (Ariaratnam et al., 2001; Davies et al., 2001; Salman and Salem, 2012). This way, inspection planning can be focused on potentially critical locations and in turn reduce the number of emergency repairs.

One of the promising methods identified in studies for developing an accurate probabilistic model is binary logistic regression, which allows the use of multiple predictor variables to estimate the probability of an event occurring. Pipe section data found in typical sewer system historical database records, including age, material, diameter, and waste type, were typically used as predictor variables. The event, or response variable, was typically either identified as the pipe section structural condition (Ariaratnam et al., 2001) or severity of potential failure modes (Davies et al., 2001). The response variables had to be converted to binary response variables in order to meet the requirements of the binary logistic regression method. To accomplish this, one study simplified a pipe section structural deterioration integer scale of 1-5 to sections with a level of 5 would be assigned a binary rating of 1 and sections with any other condition level would be assigned a binary rating of 0 (Ariaratnam et al., 2001). A similar simplification was applied in the study that used failure mode ratings (Davies et al., 2001).

The logit function used in the logistic regression can be utilized to calculate the estimated probability of an event occurring, $f(z)$ (Ariaratnam et al., 2001). Through this approach, the estimated probability

$$f(z) = \frac{1}{1+e^{-z}} \tag{A.53}$$

where z is defined as

$$z = \beta_0 + \sum_{i+1}^{k} \beta_i X_i \quad \text{(A.54)}$$

where β_0 is a constant, X_i is the i^{th} predictor variable and β_i is the regression coefficient associated with X_i.

The remaining processes for creating the final regression model involve simplification and validation. First, the model was iteratively simplified based on the premise of reducing the number of insignificant predictor variables and improving the overall model based on Akaike Information Criterion (AIC) values. One of the methods to validate the probabilistic models in these studies was to calculate the sensitivity, specificity, and predicted value of a positive result of a model (PV+) (Salman and Salem, 2012). These statistical measures allow for the comparison between observed events and events predicted by the model. Each of these tests provides a percentage score that can be used to compare the predictive accuracy of different predictive models. In the Salman and Salem (2012) study, two types of logistic regression models were developed and the model with the best percentage scores among the three statistical measures discussed here was considered to be the best model. Additionally, 80% of the overall dataset, the calibration set, was used to develop the logistic model and the remaining 20% of the overall dataset, the validation set, was tested with the logistic model to determine if results between the two groups would be similar. This grouping test can be used to determine if the logistic model over-fits the dataset used to develop the original model, or if it is expected to perform well on other datasets.

Each of the validation methods are based on post-test terminology, which are referred to as: true positive (TP), true negative (TN), false positive (FP), and false negative (FN) (Glasser, 2008). A true positive is when an event is observed and a model also predicted that the event would occur. A true negative is when an event does not occur and the model correctly predicted that the event would not occur.

A false positive is when an occurrence of an event was not observed, but the model incorrectly predicted that the event would occur. Likewise, a false negative is when an occurrence of an event was observed, but the model predicted that the event would not occur. These statistics can be assembled into a table, called a confusion matrix. An example of the format of a confusion matrix is shown in Table A.35, where a value of 0 represents an event not occurring, while a value of 1 represents an event occurring. Sensitivity, specificity, and the predicted value of a positive result are computed from the values in the confusion matrix. Sensitivity is the percentage of correctly

Table A.35: Example of a Confusion Matrix, adapted from Salman and Salem, 2012

Observed Condition	**Predicted Condition**	
	0	1
0	TN	FP
1	FN	TP

predicted event occurrences among the total instances of actual occurrences and is determined as

$$\frac{TP}{TP+FN} \qquad \text{(A.55)}$$

Specificity is the percentage of correctly predicted event non-occurrences among the total instances of actual non-occurrences and is determined as

$$\frac{TN}{TN+FP} \qquad \text{(A.56)}$$

The predicted value of a positive result (PV+) is the percentage of correctly predicted event occurrences among all predicted event occurrences and is determined as

$$\frac{TP}{TP+FP} \qquad \text{(A.57)}$$

For all of these statistical measures, a greater percentage score reflects stronger predictive accuracy of the statistical model. However, by examining statistical measures, such as sensitivity and specificity, individually, one may examine how well the binary logistic model performs for the event occurrence and non-occurrence separately. To illustrate the process of comparing predictive models, take for example the confusion matrix developed for logistic binary regression model for predicting the deterioration states of pipe sections in Table A.36.

Table A.36: Confusion Matrix for a Binary Logistic Regression Model for Predicting Critical Pipe Sections, adapted from Salman and Salem 2012

Observed Condition	**Predicted Condition**		**Correct Prediction (%)**
	0	1	
0	4,683	1,187	79.8
1	1,612	1,616	50.1

Sensitivity of the binary logistic model is

$$\frac{1{,}616}{1{,}616+1{,}612} = 50.1\% \qquad \text{(A.55)}$$

while the specificity is

$$\frac{4683}{4{,}683+1{,}187} = 79.8\%$$

(A.56)

and PV+ is

$$\frac{1{,}616}{1{,}616+1{,}187} = 57.7\%$$

(A.57)

The results of the binary logistic regression predictive accuracy tests were compared with test results of the multinomial logistic regression model, and the predictive accuracy for the binary regression were higher in two of the three tests (specificity and PV+). Therefore it was concluded that binary regression was a better model than multinomial regression for predicting sewer pipe conditions.

Works Cited

Adams, P., Aktan, A. E., Dubbs, N., DePriest, M., Minaie, E., Moon, F.L., and Ozalis S. (2014). NJDOT Risk-Based Prioritization of Structurally Deficient Bridges. Rutgers University. New Jersey Department of Transportation.

Abed-Al-Rahim, I.J. and Johnson, D.W. (1991). Analysis of relationships Affecting Bridge Deterioration and Improvement. Final Report NC / R&D / 93-001/. North Carolina Department of Transportation. Raleigh, North Carolina.

Amekudzi, A. and Meyer, M. (2011). Best Practices in Selecting Performance Measures and Standards for Effective Asset Management. Report FHWA-GA-11-0903. /Georgia Department of Transportation. Forest Park, GA.

American Association of State Highway and Transportation Officials. (2008). Bridging the Gap: Restoring and Rebuilding the Nation's Bridges. AASHTO. Available at:

https://www.infrastructureusa.org/wp-content/uploads/2010/08/bridgingthegap.pdf. Accessed May 2019.

American Society of Civil Engineers (2016). Failure to act: Closing the infrastructure investment gap for America's economic future. ASCE. Available at: https://www.infrastructurereportcard.org/wp-content/uploads/2016/10/ASCE-Failure-to-Act-2016-FINAL.pdf. Accessed May 2019.

American Society of Civil Engineers (2017). 2017 Infrastructure Report Card. Available at: https://www.infrastructurereportcard.org/. Accessed May 2019.

Ariaratnam, S. T., El-Assaly, A., and Yang, Y. (2001). "Assessment of infrastructure inspection needs using logistic models." Journal of Infrastructure Systems, 7(4), 160–165.

Bacheson, E., Meredith, C., Roda, A., Herning, G., and Liu, H. (2014). FHWA Audit Review and BrM Version 5.2.2 Guidance. Center for Advanced Infrastructure and Transportation. New Jersey Department of Transportation. RU435056-7.

Bhushan, N. and Rai, K. (2004). Strategic Decision Making: Applying the Analytical Hierarchy Process. Springer-Verlag London, Ltd.

Cavalline, T.L., Whelan, M.J., Tempest, B.Q., Goyal, R., and Ramsey, J. D. (2015). Determination of Bridge Deterioration Models and Bridge User Costs for the NCDOT Bridge Management System. Report FHWA/NC/2014-07. North Carolina Department of Transportation. Raleigh, North Carolina.

Chen, C. and Johnson, D.W. (1987). Bridge Management Under a Level of Service Concept Providing Optimum Improvement Action, Time, and Budget Prediction. Report FHWA/NC/88-004. North Carolina Department of Transportation, Raleigh, North Carolina.

Colorado Department of Transportation (2017). Transportation Planning in Colorado. CDOT Planning Manual. Denver Colorado. Available at: https://www.codot.gov/programs/planning/documents/planning-partners/planning-manual.

Dahlgren, J., Robert H., Katz, A., Williams, J., and Malchow, M. (2004). Transportation Benefit-Cost Analysis. Transportation Benefit-Cost Analysis. Available at: http://bca.transportationeconomics.org/ Accessed May 2019.

Davies, J., Clarke, B., Whiter, J., Cunningham, R., and Leidi, A. (2001). "The structural condition of rigid sewer pipes: a statistical investigation." Urban Water, 3(4), 277–286.

Dickey, J. W., and Watts, T. M. (1978). Analytical Techniques in Urban and Regional Planning. McGraw-Hill Book Co., Inc., New York, New York.

Duncan, S.A. and Johnson, D.W. (2002). Bridge Management System Update. Final Report FHWA / NC / 2005-06, North Carolina Department of Transportation, Raleigh, North Carolina.

Farrar, M. M. and Newton, B. (2014). "Perspective: The AASHTO Manual for Bridge Element Inspection." ASPIRE. Winter 2014.

Federal Highway Administration. (1995). Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. U.S. Department of Transportation Federal Highway Administration. Office of Engineering Bridge Division.

Federal Highway Administration. (2012). Moving Ahead for Progress in the 21st Century (MAP-21). Available at: https://www.fhwa.dot.gov/map21/

Florida Department of Transportation. (2012). Prioritizing Florida's Highway Investments 2012-2013. Florida Department of Transportation, Tallahassee, Florida.

Garrett, P. (2012). Priority Replacement Index Definition. Email message to Whelan, M., and Cavalline, T. August 2015.

Glasser, S. P. (2008). Research methodology for studies of diagnostic tests. In Essentials of Clinical Research. Springer.

Harris, T. and Laipply, J. (2013). Bridge Enterprise Workshop. Colorado Bridge Enterprise Memorandum. May 3, 2013. Colorado Department of Transportation. Denver, Colorado.

Hearn, G., Juntunen, D., Ahmad, A., and Johnson, B. (2013). "Performance Measures for Bridge Preservation." Proceedings of the 92nd Transportation Research Board, January 2013.

Hearn, G., Pan, S., and Casey, W. (2013). "Bridge Management Practices in Idaho, Michigan, and Virginia." Proceedings of the Transportation Research Board 92nd Annual Meeting. Washington, DC.

Hopwood, T. and Oka, V.G. (1989). Development of Priority Ranking System for Bridge Rehabilitation and Replacement. Computerized Bridge Management Systems. Research Rreport KTC-89-59. Kentucky Transportation Cabinet. Lexington, Kentucky.

Howard, R.A. (1968). "The Foundation of Decision Analysis." IEEE Transaction on System Science and Cybernetics. Vol. SSC-4, No. 3, September 1968.

Johnson, M. (2008). Project Prioritization Using Multiobjective Utility Functions. Transportation

Research Circular E-C128: International Bridge and Structure Management Conference. Transportation Research Board of the National Academies, Washington DC.

Johnson, M. and Ozbek, M. (2013). "Developing Bridge Management Components that Facilitate Decision-Making." Transportation Research Record: Journal of the Transportation Research Board, No. 2360, Transportation Research Board of the National Academies, Washington, DC, 1-810.3141/2360-09.

Johnson, D. W. and Zia, P. (1984). Level of Service System for Bridge Evaluation. Transportation Research Record: Journal of the Transportation Research Board, No. 962, Transportation Research Board of the National Academies, Washington, DC, 1-8.

Keeney, R.L., and Raiffa, H. (1993). Decisions with Multiple Objectives – Preferences and Value Tradeoffs (reprint). Cambridge University Press. New York, New York.

Lane, K.M. (2016). Performance criteria and measures for prioritization of bridge replacement projects. MS Thesis. University of North Carolina at Charlotte. Charlotte, North Carolina.

Li, Z. and Sinha, K.C. (2009). "Methodology for the Determination of Relative Weights of Highway Asset Management System Goals and of Performance Measures." Journal of Infrastructure Systems, 15(2), 95-105.

Michigan Department of Transportation (2016). 2016 System Performance Measures Report. Michigan Department of Transportation. Lansing, Michigan. Available at: https://www.michigan.gov/documents/mdot/MDOT-Performance_Measures_Report_289930_7.pdf. Accessed May 2019.

Moruza, A. K., Matteo, A. D., Mallard, J. C., Milton, J. L., Nallapaneni, P. L., and Pearce, R. L. (2016). Methodology for ranking relative importance of structures to Virginia's roadway network. Report VTRC 16-R19. Virginia Department of Transportation. Richmond, Virginia.

New York State DOT (2014). New York State DOT Transportation Asset Management Plan. Available at: https://www.tamptemplate.org/wp-content/uploads/tamps/023_newyorkstatedot.pdf. Accessed May 2019.

North Carolina Department of Transportation. (2013). Strategic Transportation Investments. Available at: https://www.ncdot.gov/initiatives-policies/Transportation/stip/Pages/strategic-transportation-investments.aspx. Accessed May 2019.

North Carolina Department of Transportation. (2016). Maintenance operations and performance analysis report (MOPAR). Technical report. December 2016. Available at: https://connect.ncdot.gov/resources/Asset-Management/MSADocuments/2016%20Maintenance%20Operations%20and%20Performance%20Analysis%20Report%20(MOPAR).pdf. Accessed May 2019.

North Carolina Department of Transportation. (2018). Prioritization 5.0. Master Presentation. North Carolina Department of Transportation. Raleigh, NC. Available at: https://connect.ncdot.gov/projects/planning/MPORPODocuments/P5.0%20Master%20Presentati on%20-%20July%202018.pdf. Accessed May 2019.

North Carolina Department of Transportation. (2019). Prioritization Resources. Available at: https://connect.ncdot.gov/projects/planning/Pages/PrioritizationResources.aspx. Accessed May 2019.

Ohio Department of Transportation. (2003). Local Major Bridge Program Standard Procedure. Title 23, U.S.C., CFR-650. Standard Procedure No. 310-004(SP). Ohio Department of Transportation. Columbus, Ohio.

Oklahoma Department of Transportation. (2015). Moving Oklahoma Forward. Long Range Transportation Plan. Oklahoma City, OK.

Oregon Department of Transportation. (2015.) 2015 Bridge Condition Report. Bridge Section. Oregon Department of Transportation. Salem, Oregon.

Parlos, P. M. (2000). Multi-Criteria Decision Making Methods: A Comparative Study. Kluwer Academic Publishers. Dordrecht, The Netherlands.

Patidar, V., Labi, S., Sinha, K., and Thompson, P. (2007). NCHRP Report 590: Multi-Objective Optimization for Bridge Management Systems. Transportation Research Board. Washington, DC.

Saaty, T.L. (2008) "Decision Making with the Analytical Hierarchy Process." International Journal of Services Sciences. 1(1), 83-98.

Saaty, T.L., and Vargas, L.G. (2012). Models, Methods, Concepts & Applications of the Analytical Hierarchy Process. International Series in Operations Research & Management Science. Springer.

Saito, M. and Sinha, K. (1989). The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol 5: Priority Ranking Method. Indiana Department of Transportation. Indianapolis, Indiana.

Saito, M., and Sinha, K. (1991). "Delphi Study on Bridge Condition Rating and Effects of Improvements." Journal of Transportation Engineering. 117(3), 320-334

Salman, B. and Salem, O. (2012). "Modeling failure of wastewater collection lines using various section-level regression models. Journal of Infrastructure Systems," 18(2), 146-154.

Selin, T. (2015). Performance-Based Planning Weighting Performance Measures as a Method to Refine Project Evaluation. Cambridge Systematics, Inc.

Shepard, R.W. and Johnson, M.B. (2001). "California Bridge Health Index: A Diagnostic Tool to Maximize Bridge Longevity, Investment." TR News. No. 215. Transportation Research Board. July-August 2001.

Sinha, K. and Labi, S. (2007). Transportation Decision Making: Principles of Project Evaluation and Programming. John Wiley & Sons, Inc. Hoboken, New Jersey.

Sinha, K. C., Labi, S., McCullouch, B. G., Bhargava, A., and Bai, Q. (2009). Updating and Enhancing the Indiana Bridge Management System (BMS). Report No. FHWA/IN/JTRP-

2008/30. Indiana Department of Transportation. Indianapolis, Indiana.

Sinha, K., Patidar, V., Li, Z., Labi, S., and Thompson, P. (2009). Establishing the Weights of Performance Criteria: Case Studies in Transportation Facility Management. Journal of Transportation Engineering, 619-631. 10.1061/(ASCE)TE.1943-5436.0000039.

Sinha, K. C., Saito, M., Jiang, Y., Murthy, S., Tee, A.B, and Bowman, M.D. (1988). The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Vol. 1: The Elements of the Indiana Bridge Management System (IBMS). Publication FHWA/IN/JHRP-88/15-1. Joint Highway Research Project, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana. doi: 10.5703/1288284314154.

Skinner, D. C. (2009). Introduction to Decision Analysis: A Practitioner's Guide to Improving Decision Quality. Probabilistic Publishing.

Smith, J. (2012). "Effective Infrastructure Management Solutions Using the Analytical Hierarchy Process and Municipal DataWork (MDW)." Proceedings of the 2012 Conference of the Transportation Association of Canada Fredericton. New Brunswick.

Sobanjo, J. O. and Thompson, P. D. (2016). Implementation of the 2013 AASHTO Manual for Bridge Element Inspection. Florida Department of Transportation. Tallahassee, Florida.

Son, Y. and Sinha, K. (1997). Methodology to Estimate User Costs in Indiana Bridge Management System. Transportation Research Record: Journal of the Transportation Research Board, No. 1597, Transportation Research Board of the National Academies, Washington, D.C., 43-51.

South Carolina Department of Transportation. (2013). Act 114 Prioritization Requirements. Office of Secretary of Transportation.

South Dakota Department of Transportation (2016). Bridge Improvement Grant (BIG) Procedure. Office of Local Government Assistance. Available at www.scdot.com

Szary, P. and Roda, A.M. (2014). Bridge Resource Program. Center for Advanced Infrastructure and Transportation. New Jersey Department of Transportation. Final Report. 435056-9.

Teknomo, K. (2006) Analytical Hierarchy Process (AHP) Tutorial. http://people.revoledu.com/kardi/tutorial/AHP/Consistency.htm. Accessed May 2019.

Tennessee Department of Transportation (2018). "High Priority Bridge Replacement Program (HPBRP). Available at:

https://www.tn.gov/content/dam/tn/tdot/programdevelopment/localprograms/funding-options/High_Priority_Bridge_Replacement_Program.pdf

Vermont Agency of Transportation. (2015). Background Information Emphasis Areas and Project Prioritization. State of Vermont. Agency of Transportation. Montpelier, Vermont.

Utah Department of Transportation (2014) Bridge Management Manual. Chapter 2, Planning and Programming. Salt Lake City, Utah. Available at: https://udot.utah.gov/main/uconowner.gf?n=12590300900442134

9. Appendix B: Initial Practitioner Survey and Results

Tab 1 of Spreadsheet:

Bridge Prioritization Survey	
Please read the Survey Background description (.pdf provided with email) before responding to the surveys on the following three tabs.	
General Instructions:	
Thank you for participating in the following survey. Please read all instructions and question carefully. There are a total of four tabs in this excel survey. Three tabs contain survey questions, they are labeled:	
	Tab 2 - Direct Weighting
	Tab 3 - AHP Questions
	Tab 4 - Mid-Value Splitting
	Tab 5 - Comments and Suggestions for Performance Measures
Please be sure to answer all the questions in each tab before returning the survey spreadsheet.	
All answer boxes will be highlighted in yellow until an answer is placed (try the example cell below).	
Answer:	

Tab 2 of Spreadsheet:

Direct Weighting

Instructions:

Please insert a given weight for each performance measure. There is a total of 100 points that can be allocated to all the measures. All 100 points must be allocated across the following performance measures. Please refer to the Survey Background PDF for unfamiliar performance measure explanations.

Example:

Performance Criteria	Performance Measures	Weight
Infrastructure Condition	Deck Condition	10

Performance Criteria	Performance Measures	Weight
Infrastructure Condition	Deck Condition Rating	
	Superstructure Condition Rating	
	Substructure Condition Rating	
	Element Health Index	
Benefit-Cost	Benefit-Cost	
Safety	Crash Density	
	Crash Severity	
	Critical Crash Rate	
Congestion Reduction	Existing Volume	
	Existing Volume / Capacity	
Vulnerability	Scour Vulnerability	
	Fracture Critical Vulnerability	
	Overload Vulnerability	
Economic Vitality	Detour Length	
Freight Mobility	Truck Volume (ADTT)	
	Truck Volume / Capacity	
	Distance to Freight Terminal	
Multimodal	Volume / Capacity, if near terminal	
	Proximity to multimodal terminal	
Functionality	Clear Deck Width Priority	
	Vehicle Clearance Priority	
	Percent Left	100
	Total	0

Tab 3 of Spreadsheet:

Bridge Prioritization : Analytical Hierarchy Process

Instructions:

Please fill in each answer under the columns "more important" and "degree of importance" for each row. Each row is asking you to compare two performance measures and select which one is more important and to what degree it is more important. The degree of importance is based off the *Scale of Absolute Numbers*, displayed below.

Example:

Item A	Item B	More Important	Degree of Importance
Infrastructure Condition	Benefit-Cost	Infrastructure Condition	Strongly More Important

This answer would indicate that you feel that "Infrastructure Condition" is a more important goal than "Benefit-Cost" and that the the selected goal (Infrastructure Condition) is strongly more important to consider in prioritization than the other goal ("Benefit-Cost")

Degree of Importance Ranking

Intensity of Importance	Explanation
1	Goal/Measures are equally important
2	Goal/Measure is slightly more important
3	Goal/Measure is moderately more important
4	Goal/Measure is strongly more important
5	Goal/Measure is extremely more important

Part 1: Performance Criteria

Item A	Item B	More Important	Degree of Importance
Infrastructure Condition	Benefit-Cost		
Infrastructure Condition	Safety		
Infrastructure Condition	Congestion Reduction		
Infrastructure Condition	Vulnerability		
Infrastructure Condition	Economic Vitality		
Infrastructure Condition	Freight Mobility		
Infrastructure Condition	Multimodal		
Infrastructure Condition	Functionality		
		More Important Goal	Degree of Importance
Benefit-Cost	Infrastructure Condition		
Benefit-Cost	Safety		
Benefit-Cost	Congestion Reduction		
Benefit-Cost	Vulnerability		
Benefit-Cost	Economic Vitality		
Benefit-Cost	Freight Mobility		
Benefit-Cost	Multimodal		
Benefit-Cost	Functionality		
		More Important Goal	Degree of Importance
Safety	Infrastructure Condition		
Safety	Benefit-Cost		
Safety	Congestion Reduction		
Safety	Vulnerability		
Safety	Economic Vitality		
Safety	Freight Mobility		
Safety	Multimodal		
Safety	Functionality		

Tab 3 of Spreadsheet (Continued):

		More Important Goal	Degree of Importance
Congestion Reduction	Infrastructure Condition		
Congestion Reduction	Benefit-Cost		
Congestion Reduction	Safety		
Congestion Reduction	Vulnerability		
Congestion Reduction	Economic Vitality		
Congestion Reduction	Freight Mobility		
Congestion Reduction	Multimodal		
Congestion Reduction	Functionality		
		More Important Goal	Degree of Importance
Vulnerability	Infrastructure Condition		
Vulnerability	Benefit-Cost		
Vulnerability	Safety		
Vulnerability	Congestion Reduction		
Vulnerability	Economic Vitality		
Vulnerability	Freight Mobility		
Vulnerability	Multimodal		
Vulnerability	Functionality		
		More Important Goal	Degree of Importance
Economic Vitality	Infrastructure Condition		
Economic Vitality	Benefit-Cost		
Economic Vitality	Safety		
Economic Vitality	Congestion Reduction		
Economic Vitality	Vulnerability		
Economic Vitality	Freight Mobility		
Economic Vitality	Multimodal		
Economic Vitality	Functionality		
		More Important Goal	Degree of Importance
Freight Mobility	Infrastructure Condition		
Freight Mobility	Benefit-Cost		
Freight Mobility	Safety		
Freight Mobility	Congestion Reduction		
Freight Mobility	Vulnerability		
Freight Mobility	Economic Vitality		
Freight Mobility	Multimodal		
Freight Mobility	Functionality		
		More Important Goal	Degree of Importance
Multimodal	Infrastructure Condition		
Multimodal	Benefit-Cost		
Multimodal	Safety		
Multimodal	Congestion Reduction		
Multimodal	Vulnerability		
Multimodal	Economic Vitality		
Multimodal	Freight Mobility		
Multimodal	Functionality		
		More Important Goal	Degree of Importance
Functionality	Infrastructure Condition		
Functionality	Benefit-Cost		
Functionality	Safety		
Functionality	Congestion Reduction		
Functionality	Vulnerability		
Functionality	Economic Vitality		
Functionality	Freight Mobility		
Functionality	Multimodal		

Tab 3 of Spreadsheet (Continued):

Part 2: Performance Measures			
Item A	**Item B**	**More Important**	**Degree of Importance**
Deck Condition	Superstructure Condition Rating		
Deck Condition	Substructure Condition Rating		
Deck Condition	Element Health Index		
		More Important Measure	Degree of Importance
Superstructure Condition Rating	Deck Condition		
Superstructure Condition Rating	Substructure Condition Rating		
Superstructure Condition Rating	Element Health Index		
		More Important Measure	Degree of Importance
Substructure Condition Rating	Deck Condition		
Substructure Condition Rating	Superstructure Condition Rating		
Substructure Condition Rating	Element Health Index		
		More Important Measure	Degree of Importance
Element Health Index	Deck Condition		
Element Health Index	Superstructure Condition Rating		
Element Health Index	Substructure Condition Rating		
		More Important Measure	Degree of Importance
Crash Density	Crash Severity		
Crash Density	Critical Crash Rate		
		More Important Measure	Degree of Importance
Crash Severity	Crash Density		
Crash Severity	Critical Crash Rate		
		More Important Measure	Degree of Importance
Critical Crash Rate	Crash Density		
Critical Crash Rate	Crash Severity		
		More Important Measure	Degree of Importance
Existing Volume	Existing Volume / Capacity		
		More Important Measure	Degree of Importance
Scour Vulnerability	Fracture Critical Vulnerability		
Scour Vulnerability	Overload Vulnerability		
		More Important Measure	Degree of Importance
Fracture Critical Vulnerability	Overload Vulnerability		
Fracture Critical Vulnerability	Scour Vulnerability		
		More Important Measure	Degree of Importance
Overload Vulnerability	Fracture Critical Vulnerability		
Overload Vulnerability	Scour Vulnerability		
		More Important Measure	Degree of Importance
Truck Volume	Truck Volume / Capacity		
Truck Volume	Distance to Freight Terminal		
		More Important Measure	Degree of Importance
Truck Volume / Capacity	Truck Volume		
Truck Volume / Capacity	Distance to Freight Terminal		
		More Important Measure	Degree of Importance
Distance to Freight Terminal	Truck Volume		
Distance to Freight Terminal	Truck Volume / Capacity		
		More Important Measure	Degree of Importance
Volume / Capacity, if near terminal	Proximity to multimodal terminal		
		More Important Measure	Degree of Importance
Clear Deck Width Priority	Vehicle Clearance Priority		

Tab 4 of Spreadsheet:

Mid-Value Splitting Technique for Condition Ratings

Instructions:

Please read each question and answer each question in the order they are arranged. Note that different options will be available based on how you answered the previous question.

Example:

At what condition rating, X, would you be equally satisfied with the improvement in condition from 0 to X,as you would be with an improvement in the condition rating from X to 9?

Options:								
	1	2	3	4	5	6	7	8
Answer:	4							

Please Note: Subsequent questions are based on the answer to the prior question. You must answer the questions in order since your answer populates the "0" in the next question and affects conditional formatting on the acceptable range of responses.

Deck Condition

Deck Condition Rating - Question 1

At what deck condition rating, X, would you be equally satisfied with the improvement in deck condition from 0 to X,as you would be with an improvement in the deck condition rating from X to 9?

Options:								
	1	2	3	4	5	6	7	8
Answer:								

Deck Condition Rating - Question 2

At what deck condition rating, X, would you be equally satisfied with the improvement in deck condtion from 0 to X, as you would be in improvement in deck condition rating X to 0?

Options:								
	[redacted]							
Answer:								

Deck Condition Rating - Question 3

At what deck condition rating, X, would you be equally satisfied with the improvement in deck condtion from 0 to X, as you would be in improvement in deck condition rating X to 9?

Options:								
	1	2	3	4	5	6	7	8
Answer:								

Tab 4 of Spreadsheet (Continued):

Deck Condition Rating - Question 4

Consistency check: In general, are you equally satisfied with an deck condtion improvement from 0 to 0
as you are in a deck condition improvement from 0 to 0?

If "Yes", then move to the next question.
If "No" , then revise previous answers for deck condition.

Superstructure Condition

Superstructure Condition Rating - Question 1

At what superstructure condition rating, X, would you be equally satisfied with the improvement in
from 0 to X,as you would be with an improvement in the superstructure condition rating from X to 9?

Options:

1	2	3	4	5	6	7	8

Answer:

Superstructure Condition Rating - Question 2

At what superstructure condition rating, X, would you be equally satisfied with the improvement in
from 0 to X, as you would be in improvement in superstructure condition rating X to 0?

Options:

[redacted]

Answer:

Superstructure Condition Rating - Question 3

At what superstructure condition rating, X, would you be equally satisfied with the improvement in
from 0 to X, as you would be in improvement in superstructure condition rating X to 9?

Options:

1	2	3	4	5	6	7	8

Answer:

Superstructure Condition Rating - Question 4

Consistency check: In general, are you equally satisfied with an superstructure condtion improvement from 0 to 0
as you are in a superstructure condition improvement from 0 to 0?

If "Yes", then move to the next question.
If "No" , then revise previous answers for superstructure condition.

Tab 4 of Spreadsheet (Continued):

Substructure Condition

Substructure Condition Rating - Question 1

At what substructure condition rating, X, would you be equally satisfied with the improvement in substructure from 0 to X,as you would be with an improvement in the substructure condition rating from X to 9?

Options:

	1	2	3	4	5	6	7	8

Answer:

Substructure Condition Rating - Question 2

At what substructure condition rating, X, would you be equally satisfied with the improvement in substructure from 0 to X, as you would be in improvement in substructure condition rating X to 0?

Options:

[redacted]

Answer:

Substructure Condition Rating - Question 3

At what substructure condition rating, X, would you be equally satisfied with the improvement in substructure from 0 to X, as you would be in improvement in substructure condition rating X to 9?

Options:

	1	2	3	4	5	6	7	8

Answer:

Substructure Condition Rating - Question 4

Consistency check: In general, are you equally satisfied with an substructure condtion improvement from 0 to 0 as you are in a substructure condition improvement from 0 to 0?

If "Yes", then move to the next part of survey.
If "No" , then revise previous answers for substructure condition.

Tab 5 of Spreadsheet:

Comments and Suggestions for Performance Measures

Instructions:

The performance goals and measures proposed and included in this survey were based on the overarching STI and MAP-21 criteria and the performance metrics utilized in Prioritization 4.0. However, bridge replacements are uniquely different from STI projects. While there is a desire to express STI goals in the prioritization, they only should be included to the extent that they are valued. This survey is intended to aid in understanding this extent.

Early feedback on the survey has suggested that there are other factors that should be incorporated into the prioritization formula that hasn't been considered. For instance, the extent that a structure has been a maintenance burden has been suggested as an important factor to consider. Using data on the number of critical finds, priority maintenance, and routine maintenance issues from the WIGINS platform, the research team may be able to develop a performance measure that incorporates an indication of maintenance burden into the prioritization formula.

In the space provided below, please provide any comment you would like on the survey. In particular, suggestions on any performance measures or criteria that are important to prioritization of bridge replacement projects that you feel are being overlooked by the research team would be helpful.

Response:

Comments Received:

Respondent A: "We always review our list of possible bridge replacements with our field supervisors to get their input because they are well aware of the recurring issues on bridges that have a high number of cases of maintenance. Many times the types of priority maintenance issues are traffic related (accidents that cause rail damage) and are more easily addressed by maintenance crews than foundations issues which is the first rating that we look at to determine priorities. A bridge with a poor substructure rating is much more difficult to maintain than one that only has deck issues."

"Another item that we always look at is the network of bridges around the possible bridge replacement. We try to answer the questions "if this bridge goes out, how big of a priority will it be to the local network? Would it have a bigger impact than another bridge in the same area that has to be closed down? Which bridge in the network would make it easier to replace other bridges in the area if it was replaced/fixed first?". Sometimes the answers to those questions is to replace a slightly better bridge in that network because having a good bridge in that location makes it easier on the traveling public (reduces detour lengths) when the other bridges are replaced. The main reason for that decision is because we have a division policy to detour traffic only on routes that don't have a posted bridge or we only detour traffic on paved roads unless both bridges are located on un-paved roads."

Respondent B: None

Respondent C: None

Direct Weighting Responses

Performance Measures	Survey 1	Survey 2	Survey 3	Mean
Infrastructure Condition	**60**	**28**	**44**	**44.0**
Deck Condition Rating	20	5	4	9.7
Superstructure Condition Rating	20	8	18	15.3
Substructure Condition Rating	20	10	22	17.3
Element Health Index	0	5	0	1.7
Benefit-Cost	**0**	**10**	**2**	**4.0**
Benefit-Cost	0	10	2	4.0
Safety	**0**	**8**	**2**	**3.3**
Crash Density	0	2	2	1.3
Crash Severity	0	4	0	1.3
Critical Crash Rate	0	2	0	0.7
Congestion Reduction	**0**	**10**	**4**	**4.7**
Existing Volume	0	6	2	2.7
Existing Volume / Capacity	0	4	2	2.0
Vulnerability	**20**	**12**	**21**	**17.7**
Scour Vulnerability	5	2	5	4.0
Fracture Critical Vulnerability	10	4	8	7.3
Overload Vulnerability	5	6	8	6.3
Economic Vitality	**5**	**10**	**2**	**5.7**
Detour Length	5	10	2	5.7
Freight Mobility	**5**	**12**	**6**	**7.7**
Truck Volume (ADTT)	5	6	3	4.7
Truck Volume / Capacity	0	4	3	2.3
Distance to Freight Terminal	0	2	0	0.7
Multimodal	**0**	**4**	**0**	**1.3**
Volume / Capacity, if near terminal	0	2	0	0.7
Proximity to multimodal terminal	0	2	0	0.7
Functionality	**10**	**6**	**19**	**11.7**
Clear Deck Width Priority	5	4	14	7.7
Vehicle Clearance Priority	5	2	5	4.0

Analytical Hierarchy Process Responses

Performance Criteria Comparisons

Respondent 1:

	Infrastructure Condition	Benefit-Cost	Safety	Congestion Reduction	Vulnerability	Economic Vitality	Freight Mobility	Multimodal	Functionality
Infrastructure Condition	1	1/9	1/7	1/7	1/7	1/7	1/7	1/9	1/5
Benefit-Cost	9	1	9	7	7	5	3	3	7
Safety	7	1/9	1	1/7	5	1/5	1/7	1/9	1/5
Congestion Reduction	7	1/5	5	1	5	1/5	1/3	1/5	5
Vulnerability	5	1/7	1/5	1/5	1	1/5	1/5	1/7	1
Economic Vitality	7	1/5	7	5	5	1	1/3	1/3	5
Freight Mobility	7	1/5	5	5	5	5	1	1/3	5
Multimodal	7	1/3	7	5	5	5	3	1	5
Functionality	7	1/7	1/7	1/7	1/5	1/5	1/5	1/5	1

Respondent 2:

	Infrastructure Condition	Benefit-Cost	Safety	Congestion Reduction	Vulnerability	Economic Vitality	Freight Mobility	Multimodal	Functionality
Infrastructure Condition	1	1/5	1/7	1/3	1/5	3	1/5	1/9	1/7
Benefit-Cost	1/5	1	1/9	1/9	1/9	1	1/3	1/9	1/7
Safety	7	9	1	1/3	3	9	1	1/3	1
Congestion Reduction	3	9	3	1	1/3	9	1/3	1/5	1/3
Vulnerability	5	9	1/3	3	1	9	1	1/3	1/3
Economic Vitality	1/3	1	1/9	1/9	1/9	1	1/9	1/7	1/9
Freight Mobility	5	7	1	3	1	9	1	1/3	1/3
Multimodal	9	9	3	5	3	7	3	1	3
Functionality	7	7	1	3	3	9	3	1/3	1

Respondent 3:

	Infrastructure Condition	Benefit-Cost	Safety	Congestion Reduction	Vulnerability	Economic Vitality	Freight Mobility	Multimodal	Functionality
Infrastructure Condition	1	1/7	1/3	1/7	1/7	1/7	1/7	1/7	1/3
Benefit-Cost	7	1	5	5	7	1	1	1/3	5
Safety	3	1/5	1	5	7	1/3	1/3	1/5	3
Congestion Reduction	7	1/5	5	1	5	1/3	1/5	1/3	5
Vulnerability	7	1/7	1/7	1/7	1	1/5	1/5	1/7	1
Economic Vitality	7	1	5	5	5	1	1	1/5	7
Freight Mobility	7	1	5	5	5	1	1	1/5	5
Multimodal	9	3	5	5	5	1	1	1	7
Functionality	1	1/7	1/7	1/5	1/7	1/5	1/5	1/7	1

10. Appendix C: Final Practitioner Survey and Results

NCDOT Performance Criteria and Measures Survey

As a component of RP2016-05, NCDOT is seeking to develop a new index for the BMS to identify bridges that are most likely to be selected for replacement based on their current condition, characteristics, past history, and extent of maintenance needs. This index will use information, ratings, and maintenance data available in the AgileAssets management system to evaluate the trade-offs between potential bridge replacement projects in order to predict future replacements and associated funding needs. In order to develop this index, information is needed on the relative importance of each of these measures, and their risks and trade-offs, considered in the decision to select a bridge for replacement.

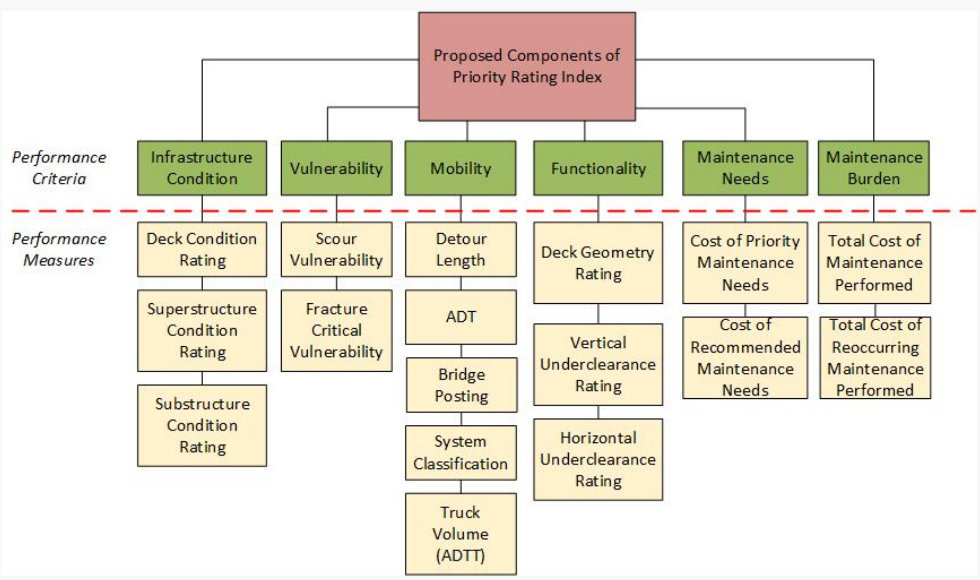
Please carefully consider the questions in the following survey and provide a response that reflects your own preferences and risk attitudes related to the selection of bridge replacement projects. Thank you for your time, insight, and assistance!

Email: [?]

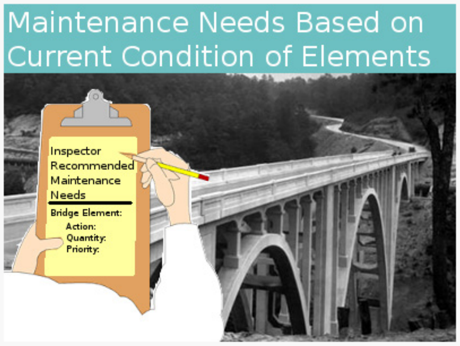
Continue to Survey | Continue Saved Survey

NCDOT Performance Criteria and Measures Survey

This Practitioner Survey was developed under NCDOT Research Project 2016-05 to determine the relative importance of the various conditions and factors that you may be considering when selecting bridge replacement projects. The intent is to develop a replacement for the current Priority Replacement Index (PRI) that better reflects the actual preferences of NCDOT decision-makers and allows for the Bridge Management System (BMS) to better anticipate the bridge replacement projects that are most likely to be selected.

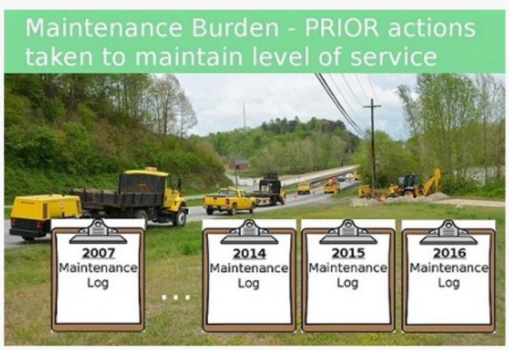


The performance measures listed under the first four performance criteria are conventional measures that are readily available in the BMS and have previously been used within prioritization formulas developed both within NCDOT and by other states. The final two performance criteria, Maintenance Needs and Maintenance Burden, incorporate new performance measures developed through the current research effort. An explanation of these performance criteria and measures is provided below:



Maintenance Needs: This performance criterion aims to reflect the current level of intervention needed to restore the structure to an adequate level of service. It is based on the Inspector Recommended Maintenance Needs developed through element-level ratings of each structure. The performance measures developed to quantify this performance criterion are as follows:

- ***Cost of Priority Maintenance Needs***: This performance measure is the total cost of all priority maintenance needs for the structure. It is obtained by summing the product of the quantities of priority maintenance needs with the unit cost for each associated maintenance action.
- ***Cost of Recommended Maintenance Needs***: This performance measure is the total cost of all recommended maintenance needs for the structure. It is obtained by summing the product of the quantities of recommended maintenance needs with the unit cost for each associated maintenance action.



Maintenance Burden: This performance criterion aims to reflect the extent to which the deteriorated condition of a bridge has become a persistent issue causing prior maintenance actions to be performed, perhaps repeatedly, in order to maintain an adequate level of service. It is based on historical records of maintenance actions performed on individual structures that are collected in the Maintenance Management System (MMS). The performance measures developed to quantify this performance criterion are as follows:

- ***Total Cost of Maintenance Performed:*** This performance measure is calculated as the total cost of all burdensome maintenance actions that have been performed on the structure over the past 10 years. Burdensome maintenance actions are maintenance and repair of any superstructure, substructure, or deck components, deck and asphalt patching, spot painting, and other actions related to repair and maintenance. Major rehabilitation investments and preservation actions are not included in this measure.
- ***Total Cost of Reoccurring Maintenance Performed***: This performance measure is calculated as the total cost of all burdensome maintenance actions that have been performed on two or more separate occasions for the same structure over the past 10 years. This measure is designed to identify structures that have required repeated intervention on a reoccurring basis in order to maintain adequate level of service.

As mentioned, the other four performance criteria are developed from conventional performance measures that are already readily available in the BMS. For reference, the descriptions of each performance measure proposed for the new priority replacement index are provided below:

Infrastructure Condition:

- ***Deck Condition Rating***: NBI Item 58: General Condition Rating for the Deck; rated on a 0 to 9 scale
- ***Superstructure Condition Rating***: NBI Item 59: General Condition Rating for the Superstructure; rated on a 0 to 9 scale
- ***Substructure Condition Rating***: NBI Item 60: General Condition Rating for the Substructure; rated on a 0 to 9 scale

Vulnerability:

- ***Scour Vulnerability***: NBI Item 113: Assessment of the scour potential for the substructure
- ***Fracture Critical Vulnerability***: NBI Item 92A: Binary classification of whether or not the structure has fracture critical details

Mobility:

- ***Detour Length***: NBI Item 19: Actual length of bridge detour. Serves as a measure of the impact of bridge closure on the community and economic vitality.
- ***ADT***: NBI Item 29: Average Daily Traffic.
- ***Bridge Posting***: NBI Item 70: Evaluation of the load capacity of the bridge relative to the state legal load.
- ***System Classification***: Categorization of the route that the bridge is located on. Could be either primary, secondary, or interstate.
- ***Truck Volume (ADTT)***: Total volume of truck traffic per day computed using NBI Item 109 (percent ADTT) and NBI Item 29 (ADT)

Functionality

- ***Deck Geometry Rating***: NBI Item 68: General Rating for Deck Geometry based on the Bridge Roadway Width and Minimum Vertical Clearance over the Bridge Roadway. Based on a 0 to 9 scale.
- ***Vertical Underclearance Rating***: NBI Item 69: General Rating for Vertical Underclearance computed using FHWA table that considers functional classification.
- ***Horizontal Underclearance Rating***: NBI Item 69: General Rating for Horizontal Underclearance computed using FHWA table that considers functional classification and whether the structure carries one-way or two-way traffic.

Progress

Next → | Save and Continue Later

NCDOT Performance Criteria and Measures Survey

1) Assign a weight for the relative importance of each of the performance criteria shown below by allocating a total of 100 points across the six criteria. Larger point assignments indicate greater importance for bridge replacement. All 100 points must be allocated across the performance criteria.

Infrastructure Condition (Deck, Superstructure, and Substructure Rating)	
Vulnerability (Scour and Fracture Critical)	
Mobility (ADT, ADTT, Bridge Posting, Detour Length, System Classification)	
Functionality (Deck Geometry Rating, Vertical Underclearance Rating, Horizontal Underclearance Rating)	
Maintenance Needs	
Maintenance Burden	
Sum:	0

Progress

← Back | Next → | Save and Continue Later

NCDOT Performance Criteria and Measures Survey

2) Assign a weight for the relative importance of each of the performance measures within the infrastructure condition performance criteria by allocating a total of 100 points across the three measures. Larger point assignments indicate greater importance for bridge replacement. All 100 points must be allocated across the performance measures.

Deck Condition Rating	
Superstructure Condition Rating	
Substructure Condition Rating	
Sum:	0

3) Assign a weight for the relative importance of each of the performance measures within the vulnerability performance criteria by allocating a total of 100 points across the two measures. Larger point assignments indicate greater importance for bridge replacement. All 100 points must be allocated across the performance measures.

Scour Vulnerability	
Fracture Critical Vulnerability	
Sum:	0

4) Assign a weight for the relative importance of each of the performance measures within the functionality performance criteria by allocating a total of 100 points across the three measures. Larger point assignments indicate greater importance for bridge replacement. All 100 points must be allocated across the performance measures.

Deck Geometry Rating	
Vertical Underclearance Rating	
Horizontal Underclearance Rating	
Sum:	0

5) Assign a weight for the relative importance of each of the performance measures within the mobility performance criteria by allocating a total of 100 points across the six measures. Larger point assignments indicate greater importance for bridge replacement. All 100 points must be allocated across the performance measures.

Detour Length	
ADT	
System Classification	
Bridge Posting	
Truck Volume (ADTT)	
Sum:	0

6) Assign a weight for the relative importance of replacing a bridge on each of the system classifications shown below by allocating a total of 100 points across the options. Larger point assignments indicate greater priority for bridge replacement. All 100 points must be allocated across the options.

Primary

Secondary

Interstate

Sum: 0

7) Assign a weight for the relative importance of each of the performance measures within the <u>maintenance needs</u> performance criteria by allocating a total of 100 points across the two measures. Larger point assignments indicate greater importance for bridge replacement. All 100 points must be allocated across the performance measures.

Total Cost of Priority Maintenance Needs

Total Cost of Recommended Maintenance Needs

Sum: 0

8) Assign a weight for the relative importance of each of the performance measures within the <u>maintenance burden</u> performance criteria by allocating a total of 100 points across the two measures. Larger point assignments indicate greater importance for bridge replacement. All 100 points must be allocated across the performance measures.

Total Cost of Burdensome Maintenance Performed over past 10 years

Total Cost of Burdensome Reoccurring Maintenance over past 10 years

Sum: 0

Progress

Back | Next | Save and Continue Later

NCDOT Performance Criteria and Measures Survey

Performance Criteria

9) Compared to <u>Infrastructure Condition</u>

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Vulnerability is…									
Mobility is…									
Functionality is…									
Maintenance Needs are…									
Maintenance Burden is…									

10) Compared to <u>Vulnerability</u>

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Mobility is…									
Functionality is…									
Maintenance Needs are…									
Maintenance Burden is…									

11) Compared to <u>Mobility</u>

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Functionality is…									
Maintenance Needs are…									
Maintenance Burden is…									

12) Compared to <u>Functionality</u>

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintenance Needs are…									
Maintenance Burden is…									

13) Compared to <u>Maintenance Needs</u>

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintenance Burden is…									

Progress

Back | Next | Save and Continue Later

NCDOT Performance Criteria and Measures Survey

Infrastructure Condition Performance Measures

14) Compared to Deck Condition Rating

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Superstructure Condition Rating is...	○	○	○	○	○	○	○	○	○
Substructure Condition Rating is...	○	○	○	○	○	○	○	○	○

15) Compared to Superstructure Condition Rating

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Substructure Condition Rating is...	○	○	○	○	○	○	○	○	○

Progress

Back | Next | Save and Continue Later

NCDOT Performance Criteria and Measures Survey

Mobility Performance Measures

16) Compared to Detour Length

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
ADT is...	○	○	○	○	○	○	○	○	○
Bridge Posting is...	○	○	○	○	○	○	○	○	○
System Classification is...	○	○	○	○	○	○	○	○	○
Truck Volume (ADTT) is...	○	○	○	○	○	○	○	○	○

17) Compared to ADT

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Bridge Posting is...	○	○	○	○	○	○	○	○	○
System Classification is...	○	○	○	○	○	○	○	○	○
Truck Volume (ADTT) is...	○	○	○	○	○	○	○	○	○

18) Compared to Bridge Posting

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
System Classification is...									
Truck Volume (ADTT) is...									

18) Compared to Bridge Posting

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
System Classification is...									
Truck Volume (ADTT) is...									

19) Compared to System Classification

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Truck Volume (ADTT) is...									

20) Compared to replacement of a bridge on a Primary route

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Replacement of a bridge on a Secondary route is ...									
Replacement of a bridge on an Interstate route is ...									

21) Compared to replacement of a bridge on a Secondary route

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Replacement of a bridge on an Interstate route is ...									

Progress

Back | Next | Save and Continue Later

NCDOT Performance Criteria and Measures Survey

Vulnerability Performace Measures

22) Compared to Scour Vulnerability

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Fracture Critical Vulnerability is...									

Functionality Performance Measures

23) Compared to Deck Geometry Rating

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Vertical Underclearance Rating is...	○	○	○	○	○	○	○	○	○
Horizontal Underclearance Rating is...	○	○	○	○	○	○	○	○	○

24) Compared to Vertical Underclearance Rating

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Horizontal Underclearance Rating is...	○	○	○	○	○	○	○	○	○

Maintenance Needs Performance Measures

25) Compared to Cost of Priority Maintenance Needs

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Cost of Recommended Maintenance Needs is...	○	○	○	○	○	○	○	○	○

Maintenance Burden Performance Measures

26) Compared to Total Cost of Burdensome Maintenance Performed over the past 10 years

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Total Cost of Reoccurring Burdensome Maintenance Performed over the past 10 years is...	○	○	○	○	○	○	○	○	○

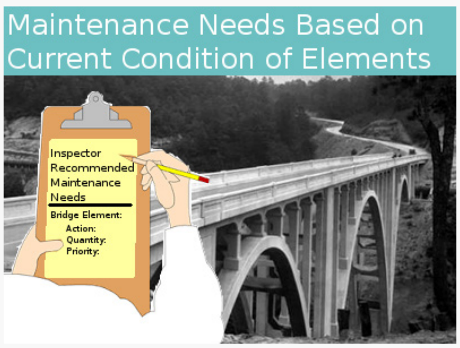
Progress

Back | Next | Save and Continue Later

NCDOT Performance Criteria and Measures Survey

Maintenance Needs

The following set of questions ask you to indicate the relative priority for bridge replacement that you associated with specific maintenance needs actions. As a reminder, maintenance needs are the current interventions that would be required in order to restore the structure to an adequate level of service.



27) Compared to a bridge with the need to Maintain Deck, a bridge with the need to

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Superstructure is...	○	○	○	○	○	○	○	○	○
Maintain Substructure Components is...	○	○	○	○	○	○	○	○	○

28) Compared to a bridge with the need to Maintain Superstructure, a bridge with the need to

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Substructure Components is...	○	○	○	○	○	○	○	○	○

29) Compared to a bridge with the need to Maintain Timber Deck, a bridge with the need to

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Steel Deck is...	○	○	○	○	○	○	○	○	○
Maintain Concrete Deck is...	○	○	○	○	○	○	○	○	○

30) Compared to a bridge with the need to Maintain Steel Deck, a bridge with the need to

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Concrete Deck is...	○	○	○	○	○	○	○	○	○

31) Compared to a bridge with the need to Maintain Timber Superstructure Components a bridge with the need to

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Steel Superstructure Components is...	○	○	○	○	○	○	○	○	○
Maintain Concrete Superstructure Components is...	○	○	○	○	○	○	○	○	○

32) Compared to a bridge with the need to Maintain Steel Superstructure Components a bridge with the need to

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Concrete Superstructure Components is...	○	○	○	○	○	○	○	○	○

33) Compared to a bridge with the need to Maintain Timber Substructure Components a bridge with the need to

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Steel Substructure Components is...	○	○	○	○	○	○	○	○	○
Maintain Concrete Substructure Components is...	○	○	○	○	○	○	○	○	○

34) Compared to a bridge with the need to Maintain Steel Substructure Components a bridge with the need to

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Concrete Substructure Components is...	○	○	○	○	○	○	○	○	○

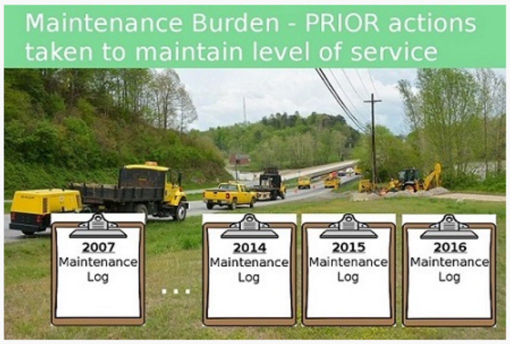
Progress

Back | Next | Save and Continue Later

NCDOT Performance Criteria and Measures Survey

Maintenance Burden

The following set of questions ask you to indicate the relative priority for bridge replacement that you associated with specific maintenance burden actions. As a reminder, maintenance burden is a measure of the prior interventions that have already been performed (potentially repeatedly) in order to maintain the structure at an adequate level of service.



35) Compared to a bridge that has a history of Maintain Superstructure Components actions, a bridge with a history of

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Deck is...	○	○	○	○	○	○	○	○	○
Maintain Substructure components is...	○	○	○	○	○	○	○	○	○

36) Compared to a bridge that has a history of Maintain Deck actions, a bridge with a history of

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Substructure components is...	○	○	○	○	○	○	○	○	○

37) Compared to a bridge that has a history of Maintain Timber Superstructure Components actions, a bridge with a history of

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Steel Superstructure Components is...	○	○	○	○	○	○	○	○	○
Maintain Concrete Superstructure components is...	○	○	○	○	○	○	○	○	○

38) Compared to a bridge that has a history of Maintain Steel Superstructure Components actions, a bridge with a history of

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Concrete Superstructure components is...	○	○	○	○	○	○	○	○	○

39) Compared to a bridge that has a history of Maintain Timber Deck actions, a bridge with a history of

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Steel Deck is...	○	○	○	○	○	○	○	○	○
Maintain Concrete Deck is...	○	○	○	○	○	○	○	○	○

40) Compared to a bridge that has a history of Maintain Steel Deck actions, a bridge with a history of

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Concrete Deck is...	○	○	○	○	○	○	○	○	○

41) Compared to a bridge that has a history of Maintain Timber Substructure Components actions, a bridge with a history of

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Steel Substructure Components is...	○	○	○	○	○	○	○	○	○
Maintain Concrete Substructure Components is...	○	○	○	○	○	○	○	○	○

42) Compared to a bridge that has a history of Maintain Steel Substructure Components actions, a bridge with a history of

	Extremely less important	Strongly less important	Moderately less important	Slightly less important	Equally as important	Slightly more important	Moderately more important	Strongly more important	Extremely more important
Maintain Concrete Substructure Components is...	○	○	○	○	○	○	○	○	○

Progress

Back | Next | Save and Continue Later

NCDOT Performance Criteria and Measures Survey

43) In the space provided below, please provide any comments you would like on the survey. In particular, suggestions on any performance measures or criteria that are important to prioritization of bridge replacement projects that you feel are being overlooked by the research team would be helpful.

Progress

Back | Finish | Save and Continue Later

Classification of Respondents (Division or Central)

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Division	Central
Division or Central	D	C	D	C	D	D	D	D	D	D	C	D	D	D	C	D	D	C	C	C	C	D	D	15	8

Question 1: Direct Weighting of Performance Criteria

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Average	Median	Std. Dev.
Infrastructure Condition	35	20	20	30	25	30	25	40	25	30	50	20	25	25	30	20	60	35	35	30	20	20	20	29.1	25.0	10.2
Vulnerability	20	15	10	20	10	20	25	10	40	10	5	17	20	18	10	20	5	5	10	20	20	20	20	16.1	18.0	7.9
Mobility	15	20	20	10	10	25	28	10	15	5	25	11	10	17	20	10	15	20	10	10	10	20	20	15.5	15.0	6.2
Functionality	20	15	20	20	5	10	2	10	10	5	5	20	10	5	10	10	10	10	15	10	15	10	5	11.0	10.0	5.4
Maintenance Needs	5	15	15	10	20	10	15	20	5	20	5	16	20	10	15	20	5	20	15	20	20	10	15	14.2	15.0	5.6
Maintenance Burden	5	15	15	10	30	5	5	10	5	30	10	16	15	25	15	20	5	10	15	10	15	20	20	14.2	15.0	7.5

Question 2: Direct Weighting of Infrastructure Condition Performance Measures

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Average	Median	Std. Dev.
Deck	10	20	20	34	30	25	25	20	15	25	10	34	25	40	26	20	20	20	40	25	20	33	50	25.5	25.0	9.6
Superstructure	35	40	35	33	30	35	25	40	35	30	40	33	35	35	37	40	60	40	30	40	40	33	25	35.9	35.0	7.0
Substructure	55	40	45	33	40	40	50	40	50	45	50	33	40	25	37	40	20	40	30	35	40	34	25	38.6	40.0	8.6

Question 3: Direct Weighting of Vulnerability Performance Measures

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Average	Median	Std. Dev.
Scour	40	20	40	40	50	60	50	40	40	30	75	45	30	40	60	20	40	50	50	30	40	50	30	42.2	40.0	12.9
Fracture Critical	60	80	60	60	50	40	50	60	60	70	25	55	70	60	40	80	60	50	50	70	60	50	70	57.8	60.0	12.9

Question 4: Direct Weighting of Functionality Performance Measures

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Average	Median	Std. Dev.
Deck Geometry Rating	30	30	30	33	20	30	20	20	15	40	10	40	35	30	35	20	30	35	50	30	20	30	33	29.0	30.0	9.0
Vertical Underclearance	40	40	50	33	60	35	60	40	50	40	70	33	25	40	35	60	60	50	30	30	40	35	33	43.0	40.0	12.1
Horiz. Underclearance	30	30	20	34	20	35	20	40	35	20	20	27	40	30	30	20	10	15	20	40	40	35	34	28.0	30.0	8.9

Question 5: Direct Weighting of Mobility Performance Measures

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Average	Median	Std. Dev.
Detour Length	15	25	10	20	30	35	5	10	10	5	10	20	15	20	10	10	30	-	20	10	10	10	10	15.5	10.0	8.4
ADT	30	20	20	20	15	20	5	20	25	25	10	20	25	13	25	25	20	-	10	25	15	10	20	19.0	20.0	6.4
System Classification	15	20	20	20	15	10	0	30	35	5	50	15	20	14	20	15	10	-	15	10	30	10	10	17.7	15.0	10.9
Bridge Posting	30	25	30	20	30	25	80	20	20	40	25	25	25	40	25	40	30	-	40	30	30	50	40	32.7	30.0	13.2
Truck Volume (ADTT)	10	10	20	20	10	10	10	20	10	25	5	20	15	13	20	10	10	-	15	25	15	20	20	15.1	15.0	5.7

Question 6: Direct Weighting of System Classifications

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Average	Median	Std. Dev.
Primary	35	30	30	30	30	35	34	30	35	40	25	33	30	35	35	40	25	35	30	40	35	33	35	33.0	34.0	4.1
Secondary	20	30	20	20	20	20	33	10	15	20	15	33	30	25	25	10	15	20	15	20	30	33	25	21.9	20.0	7.1
Interstate	45	40	50	50	50	45	33	60	50	40	60	34	40	40	40	50	60	45	55	40	35	34	40	45.0	45.0	8.4

Question 7: Direct Weighting of Maintenance Needs Performance Measures

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Average	Median	Std. Dev.
Priority Needs	75	50	60	60	75	60	40	70	65	50	60	55	70	65	60	60	80	75	75	70	60	60	70	63.7	60.0	9.7
Recommended Needs	25	50	40	40	25	40	60	30	35	50	40	45	30	35	40	40	20	25	25	30	40	40	30	36.3	40.0	9.7

Question 8: Direct Weighting of Maintenance Burden Performance Measures

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Average	Median	Std. Dev.
Burdensome	75	50	40	60	40	35	40	50	35	20	30	55	60	45	40	40	30	50	75	40	40	80	70	47.8	40.0	15.9
Reoccurring	25	50	60	40	60	65	60	50	65	80	70	45	40	55	60	60	70	50	25	60	60	20	30	52.2	60.0	15.9

Question 9: AHP Performance Criteria Comparisons to Infrastructure Condition

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Vulnerability		1/3	1/5		1/5	1/5	7	1/7	7	1/5	1/5	1/3	1/3	1/3	1/3	1	3	1/7	1/5	1/5	1/5	1	1/7
Mobility		1/3	1/3		1	1/3	7	1/5	1	1/7	1/3	1/5	1/7	1/5	3	1	7	1/5	1/5	1	1/5	1	1/5
Functionality		1/5	1		1	1/5	1	1/5	3	1/7	1/3	1	1/7	1/5	1/3	1	7	1/7	1/5	1/5	1/3	1	1/3
Maintenance Needs		1/5	3		3	1/5	1	1/7	1/3	1/3	1/3	1/3	1/3	1	1	1	7	1/5	1/5	1	1	1	1
Maintenance Burden		1/5	5		5	1/5	1	1/7	1/3	1	1/3	1/3	1/5	9	3	1	1	1/7	1/5	1/3	1/5	1	3

Question 10: AHP Performance Criteria Comparisons to Vulnerability

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Mobility			1		1	3	1	3	1/3	1/3	1/3	1/3	1/7	1/3	3	1	5	5	1/5	3	1	1	5
Functionality			5		1	1/3	1/3	3	1/3	1/3	1/5	3	1/7	1/5	3	1	7	5	1	3	3	1	3
Maintenance Needs			3		3	3	1/3	1/3	1/5	5	1/5	1	1	3	1/3	1	7	5	1/3	5	5	3	3
Maintenance Burden			5		5	3	1/3	1/5	1/5	7	1/3	1	1/3	7	1	1	3	3	1/5	3	1	3	5

Question 11: AHP Performance Criteria Comparisons to Mobility

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Functionality			1		1	1/5	1/5	1/5	3	1	1/5	5	1	1/5	1/3	1	7	1/3	1/3	3	3	1	3
Maintenance Needs			3		3	1/3	1		3	5	1/3	5	5	5	1/3	1	7	5	1/3	5	5	5	3
Maintenance Burden			7		5	1/3	1	1/7	3	7	1/3	5	3	9	1	1	7	5	1/3	3	1	3	5

Question 12: AHP Performance Criteria Comparisons to Functionality

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Maintenance Needs			1		5	3	5	1/5	1	5	1/5	1/3	5	9	1	1	9	5	1/3	5	3	5	1
Maintenance Burden			5		7	3	5	1/7	1	7	1/3	1/3	3	9	3	1	9	1/3	1/3	3	1	3	5

Question 13: AHP Performance Criteria Comparisons to Maintenance Needs

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Maintenance Burden			3		5	3	3	1/3	1	3	3	1	1/3	7	3	3	5	1/5	1/3	1/3	1/3	3	5

Question 14: AHP Performance Measure Comparisons to Deck Condition Rating

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Superstructure		5	3		1/3	3	5	5	5	5	3	1	3	1/3	5	5	9	5	1/3	5	7	1	1/3
Substructure		5	7		1/3	3	9	5	7	7	5	1	5	1/3	5	5	5	5	1/3	5	7	1	1/3

Question 15: AHP Performance Measure Comparisons to Superstructure Condition Rating

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Substructure		1	5		3	3	9	1	5	5	5	1	1/3	1/3	1	1	5	3	1	1	1	3	1

Question 16: AHP Performance Measure Comparisons to Detour Length

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
ADT					3	1/3	1	1/3	7	5	3	1	5	1/5	3	5	9	1	1/5	7	3	5	1
Bridge Posting		5			1/3	1/3	9	1/5	5	7	5	5	5	5	7	5	9	5	5	7	7	9	9
System Classification		3			1/3	1/3	1	1/5	9	1	1/3	1/5	3	1	5	5	5	5	1	1/3	7	7	1/5
Truck Volume (ADTT)					1/3	1/5	3	1/3	1	5	3	1	1	1/5	5	5	7	1	3	7	3	9	5

Question 17: AHP Performance Measure Comparison to ADT

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Bridge Posting		3			5	5	9	1/3	1/3	3	3	5	1	7	5	5	9	5	7	3	5	9	7
System Classification					3	1/3	1	1/3	5	1/5	1/3	1/5	1/3	3	1/3	1	7	5	5		7	5	1
Truck Volume (ADTT)					3	1/3	3	1	1/5	1	1/5	1	1/5	1/3	3	1	5	1/3	5	3	3	7	3

Question 18: AHP Performance Measure Comparison to Bridge Posting

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
System Classification					3	3	1/9	1	5	1/5	1/3	1/5	1/3	1/3	1	1/5	9	1/3	1/5	1/3	3	1	1/7
Truck Volume (ADTT)					3	1/3	1/3	3	1/5	1/3	1/3	1/3	1/5	1/5	5	1/5	9	1/5	1/5	5	1	1	1/5

Question 19: AHP Performance Measure Comparison to System Classification

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Truck Volume (ADTT)					5	1/3	5	3	1/7	5	1/5	5	1/3	1/3	5	1	7	1	1/5	5	1	3	5

Question 20: AHP System Classification Comparison to Primary Routes

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Secondary Route		1/3			1/5	1/5	1	1/7	1/5	1/3	1/3	1	1	1/3	1/5	1/5	5	1/5	1/5	1/5	1	1	1/5
Interstate Route		3			5	5	1	7	7	1	5	1	3	3	3	5	9	3	5	1	1	1	1/5

Question 21: AHP System Classification Comparison to Secondary Routes

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Interstate Route		5			9	7	1	9	9	3	7	1	3	5	7	9	9	5	9	7	1	1	7

Question 22: AHP Performance Measure Comparison to Scour Critical Vulnerability

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Fracture Critical		1			1	1/5	1	1	5	5	5	3	7	3	1/5	7	7	3	3	5	5	1	7

Question 23: AHP Performance Measure Comparison to Deck Geometry Rating

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Vertical Underclearance		3			5	3	9	1	7	1	5	1	1/3	5	5	7	9	3	1/3	3	3	5	1
Horiz. Underclearance		3			1	3	1	1	5	1/3	3	1/3	3	1	1/5	1	7	1/7	1/5	3	3	5	1

Question 24: AHP Performance Measure Comparison to Vertical Underclearance

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Horiz. Underclearance		1/5			5	1/3	1/5	1	1/5	1/3	1/3	1/3	5	1/5	1/5	1/5	7	1/7	1/5	1	3	1/3	

Question 25: AHP Performance Measure Comparison to Priority Maintenance Needs

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Recommended Needs		1/7			1/5	1/3	1/3	1/5	1/5	1	1/3	1/3	1/7	1/5	1/5	1/5	1/5	1/7	1/5	1/5	1/3	1/3	1

Question 26: AHP Performance Measure Comparison to Burdensome Maintenance Cost

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Reoccurring		5			5	5	1	1	5	3	1	3	1	3	5	7	9	1/7	3	1/5	3	1/3	1

Question 27: AHP Maintenance Needs Comparison to Maintain Deck

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Maintain Superstructure		3			1/3	3	1/3	5	5	3	5	1	3	1/3	7	5	7	3	1/3	7	5	1	7
Maintain Substructure		3			1/3	3	1/7	5	9	5	7	1	5	1/5	7	5	1/3	1/3	1/3	7	5	1	7

Question 28: AHP Maintenance Needs Comparison to Maintain Superstructure

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Maintain Substructure		1			1	1	1/5	1	3	3	5	1	3	1/3	1	1	1/3	1/3	1/3	1	1	1	1/3

Question 29: AHP Maintenance Needs Comparison to Maintain Timber Deck

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Maintain Steel Deck		5			7	1	1	1/3	7	5	1/3	1/3	1/3	3	1	1	7	5	3	1	3	1	5
Maintain Concrete Deck		5			7	5	1	1/7	7	5	1/3	1/5	1/3	3	7	1	7	5	5	1/3	3	1	9

Question 30: AHP Maintenance Needs Comparison to Maintain Steel Deck

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Maintain Concrete Deck		7			5	1	1	1/3	1	1	1	1/5	1	1	7	1	5	3	5	1/3	3	1	9

Question 31: AHP Maintenance Needs Comparison to Maintain Timber Superstructure

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Steel Superstructure					5	5	1	1/3	7	5	5	1/3	1/3	5	1	1	9	5	1/3	1	1	1	1
Concrete Superstructure					5	5	1	1/5	7	5	5	1/7	1/3	5	1	1	9	3	1/3	1/3	1		1

Question 32: AHP Maintenance Needs Comparison to Maintain Steel Superstructure

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Concrete Superstructure					1/3	1	1	1/3	1	1	1	1/5	1	1	1	1	1	1/3	1	1/3	1	1	1/3

Question 33: AHP Maintenance Needs Comparison to Maintain Timber Substructure

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Steel Substructure					5	7	1	1/5	1	5	5	1/3	1/3	3	1	1	9	5	1/3	1	1	1	3
Concrete Substructure					5	7	1	1/5	1	3	5	1/5	1/3	3	1	1	9	5	1/3	1/3	1	1	1/3

Question 34: AHP Maintenance Needs Comparison to Maintain Steel Substructure

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Concrete Substructure					3	1	3	1	1	1/3	1	1/5	1	1/3	1	1	1	1/3	1	1	1	1	1/3

Question 35: AHP Maintenance Burden Comparison to Maintain Superstructure

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Maintain Deck					1	1/3	1	1/3	1/5	1/3	1/3	3	1/3	3	1/3	1/5	1	1	3	1/5	1/3	1	7
Maintain Substructure					1	1	3	1/3	3	3	3	1/5	5	1/3	1	1	1/3	1/3	1/3	1	1	1	1/3

Question 36: AHP Maintenance Burden Comparison to Maintain Deck

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Maintain Substructure					3	3	5	1	7		5	1/3	7	1/5	3	5	1/3	1/3	1/3	5	5	1	1/5

Question 37: AHP Maintenance Burden Comparison to Maintain Timber Superstructure

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Steel Superstructure					5	5	1	1/3	3		1/3	1/3	1/3	3	1	1	9	5	1/3	1	1	1	7
Concrete Superstructure					5	5	1	1/3	3		1/3	1/5	1/3	3	1	1	9	5	1/3	1/3	1	1	1/3

Question 38: AHP Maintenance Burden Comparison to Maintain Steel Superstructure

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Concrete Superstructure					3	1	1	1/3	1		1	1/5	1	1/3	1	3	1		1	1/3	1	1	1/3

Question 39: AHP Maintenance Burden Comparison to Maintain Timber Deck

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Maintain Steel Deck					1	3	1	1/3	7		1/3	1/3	1/3	3	1	1	9	1	1/3	1	1	1	1
Maintain Concrete Deck					1	5	1	1/5	7		1/3	1/5	1/3	3	3	1	9	3	1/3	1/3	3	1	9

Question 40: AHP Maintenance Burden Comparison to Maintain Steel Deck

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Maintain Concrete Deck					1	3	3	1/3	1		1	1/3	1	1/3	3	1	1	5	1	1/3	3	1	7

Question 41: AHP Maintenance Burden Comparison to Maintain Timber Substructure

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Steel Substructure					5	5	1	1/3	1		1	1	1/3	3	1	1	9	5	1/3	1	3		3
Concrete Substructure					3	5	1	1/5	1		1	1/5	1/3	3	1	1	9	5	1/3	1/3	3	1	1/3

Question 42: AHP Maintenance Burden Comparison to Maintain Steel Substructure

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Concrete Substructure					1/5	1	1	1/5	1		1	1/5	1	1/3	1	1	1	1/3	1	1/3	1	1	5

Question 43: Comments

Respondent 6: Some consideration needs to be made into what type of bridge is being considered for determining the amount of maintenance needed and whether or not to perform actual maintenance on a bridge. Sometimes performing the maintenance in an appropriate manner that will actually extend the service life of the structure can come close to or exceed the cost of replacement. For instance, a small bridge with a timber deck and steel superstructure may have a failing paint system, but replacing the paint system on the bridge would most likely exceed the cost of replacing the timber deck and steel superstructure. This is because sandblasting and painting (using containment) in this matter is cost prohibitive and would exceed any unit costs that are seen on similar type projects on larger bridges. Another example of where replacement is almost always the used instead of maintenance is a bridge with a timber substructure. A bridge with a timber substructure is not very serviceable in regards to the substructure condition. Once the substructure has deteriorated there is very little that can be done to significantly extend the life of the structure, other than completely replacing the entire structure. This of course is different for concrete and steel substructures where rehabilitation methods, such as shotcrete repairs, can be used to significantly extend the service life of the structure. Consideration may need to be made at looking at a threshold for replacement versus repair costs on structures and making replacement decisions based on this criteria as well. This threshold may need to be different for different types of structures and different components of the structure. Ultimately each bridge is different in nature on many different aspects, so providing the data to the staff making these decisions is critical and can certainly help with programming the best possible bridge replacement candidates.

Respondent 7: ANY bridge with a SV posting of 20 tons or less should qualify for replacement. If Fire, EMS and school busses cannot cross the bridge I have (NCDOT has) failed the community. All bridge posted 20 tons or less should be programed for replacement in hopes they will be replaced before reaching 15 tons. Temporary Repairs should still be considered “Temporary Repairs” and trigger an SD classification. Ex: crutch bents, steel beam plating, wooden pile replacement.

Respondent 9: Consider including crash histories as a performance criteria or performance measure of the PRI. Crash history and the causes would be important in identifying and prioritizing the needed improvements and/or replacements.

Respondent 10: I will be honest with you, I consumed too much time in this survey. The end became confusing as to whether I am addressing maintenance comparisons or replacement comparisons. I believe the survey is great on the initial questions, but the relevance kept me from completing it. I feel I would be giving you inaccurate information if I continued. There are several comparisons that I make when determining the replacements and when I determine maintaining. The relevance to which component is less or more important is different from replacement and maintaining. The determination we use on maintenance is what will it take get it to a maintainable level and keeping it there. I hope the information I have given will help. Please feel free to contact me at the email provided or at ***-***-****.

Respondent 18: The survey was a bit difficult to keep straight. What is interesting though is that a poor substructure is generally an indicator that rehabilitation is likely not practical. However, immediate needs to maintain the deck and the substructure can be safety and/or load posting related and have a higher immediate priority.

Respondent 19: After all the research and surveys I'm wondering if maybe sufficiency rating is the tool we've been looking for all along....

Respondent 20: More preservation projects would be beneficial on some of the larger structures, specifically addressing spalls/rebar section loss and clean/paint structural steel. There are structures out there with these type PMs that could easily consume an entire bridge yard crew for months in order to complete. We just do not have the manpower to keep up with emergency calls, RMIP pipe replacements, pipe washouts and knock out these huge PM lists for certain structures.

Respondent 22: I primarily use the SD & FO, Sufficiency Rating, HBI, Posting, and if it is Timber or not. But always ask the County Supervisors for their input, such as: give me the top 5 worst bridges in your county(s) if you could replace them right now and $ was not an object. What bridges are working on more and more after each inspection cycle? This only works if you have people that have been working in their current county for several years and know their structures.

11. Appendix D: Linear and ECDF Value Functions for Proposed Performance Measures Computed for NCDOT Bridge Inventory

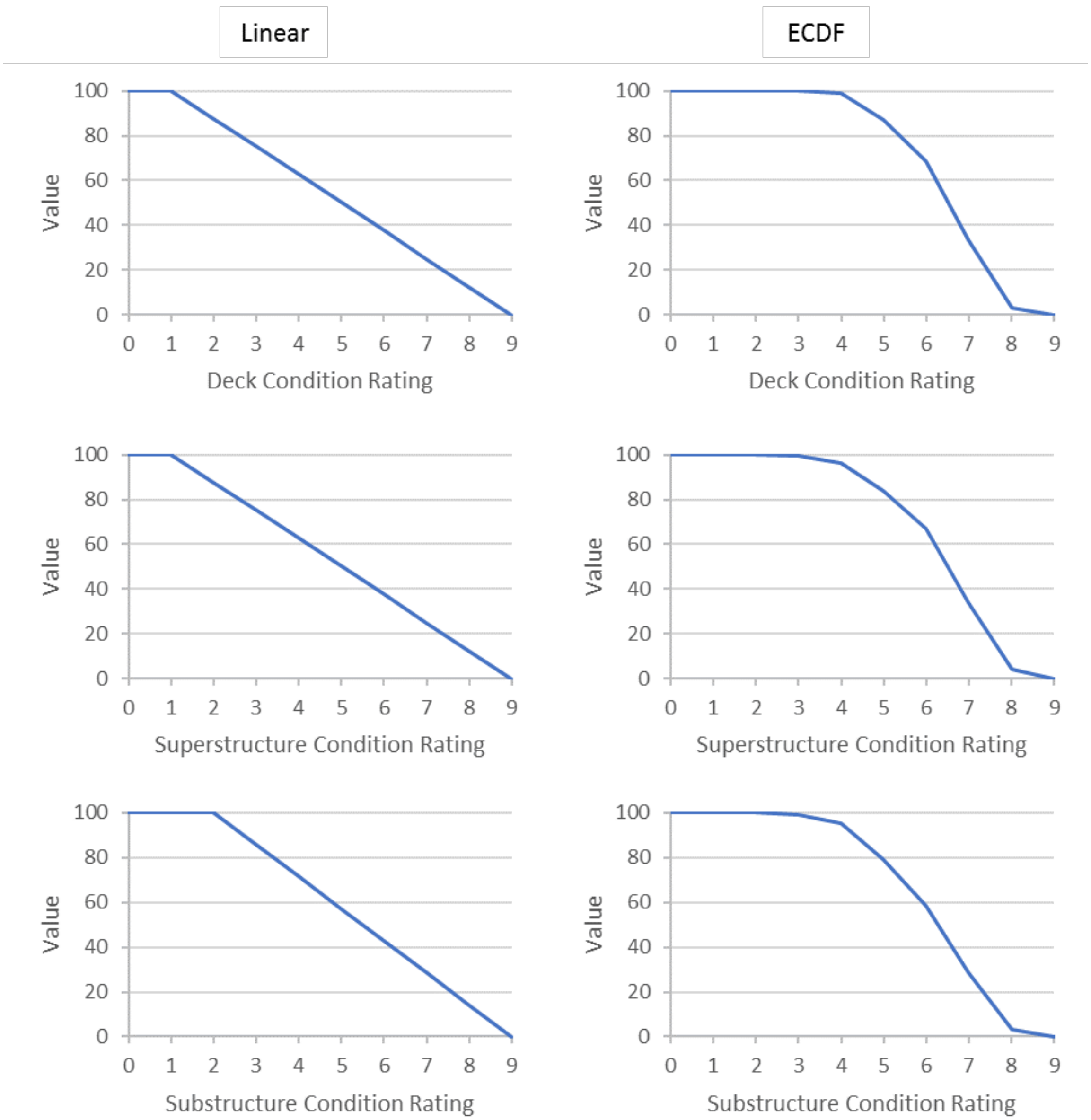


Figure B.1. Linear and ECDF Value Functions for Infrastructure Condition

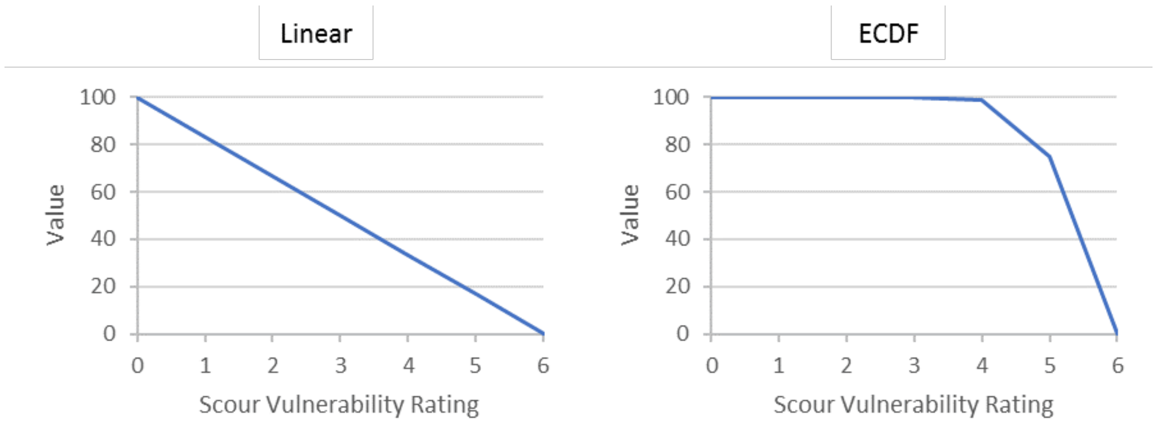


Figure B.2. Linear and ECDF Value Functions for Vulnerability

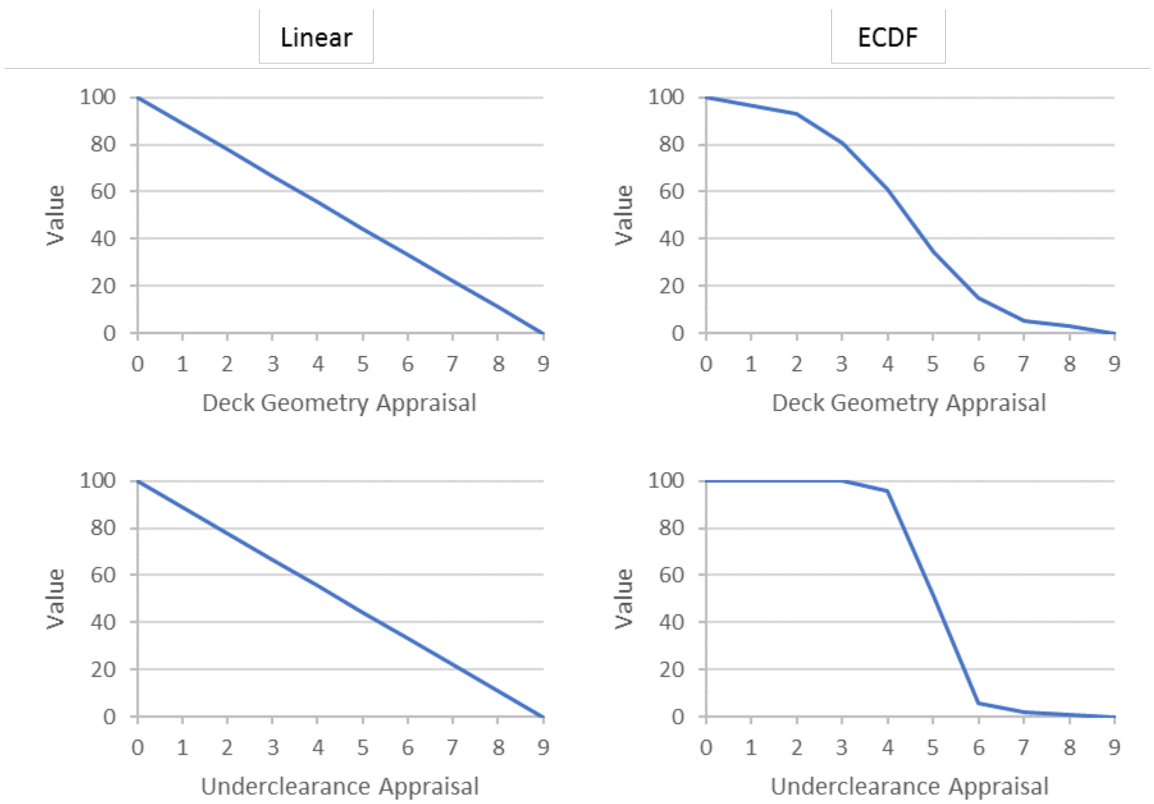


Figure B.3. Linear and ECDF Value Functions for Functionality

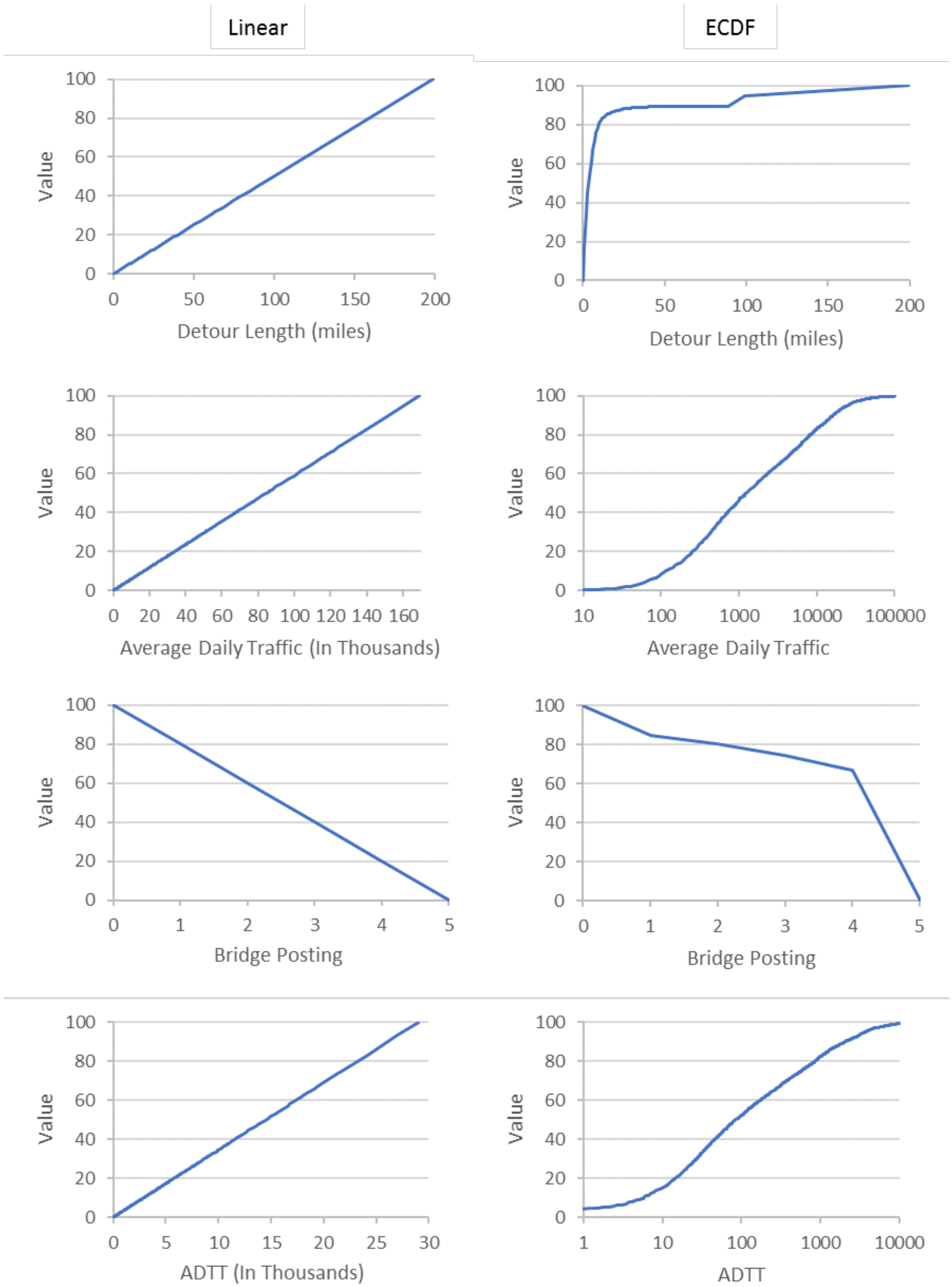


Figure B.4. Linear and ECDF Value Functions for Mobility

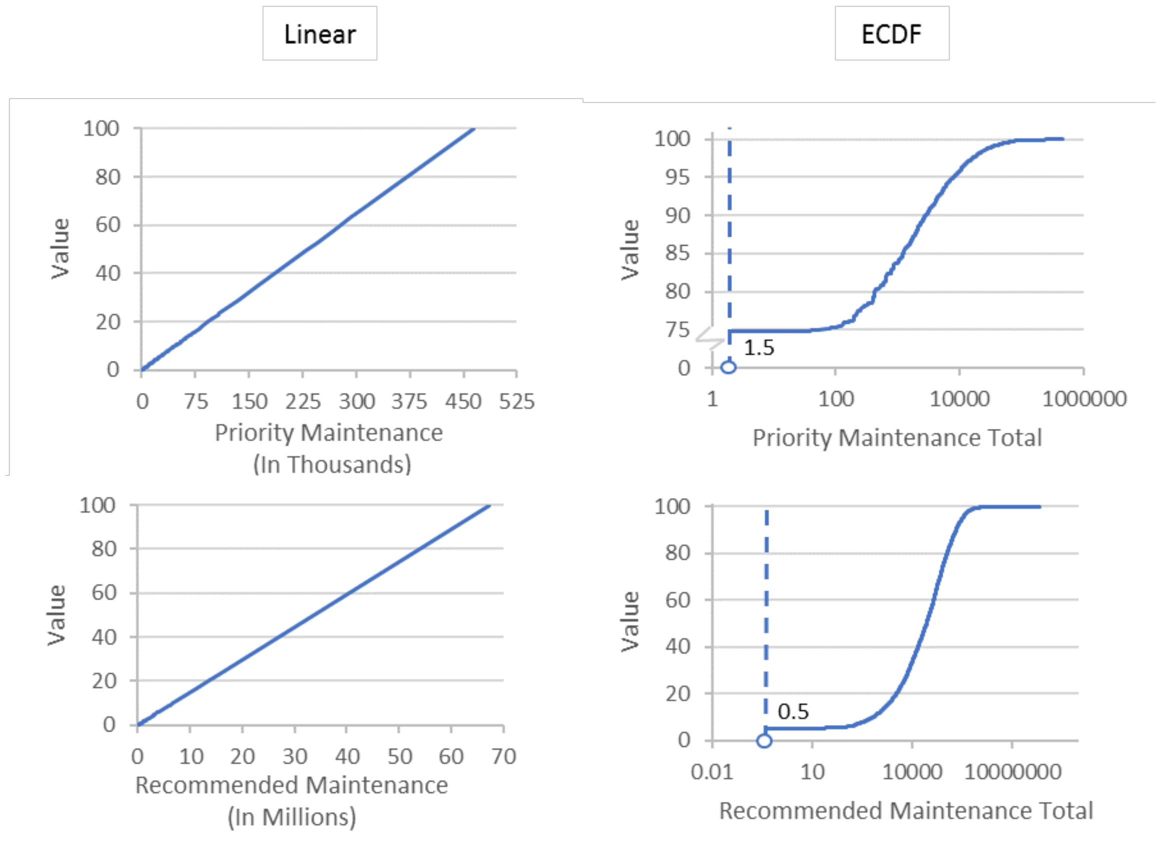


Figure B.5. Linear and ECDF Value Functions for Maintenance Needs

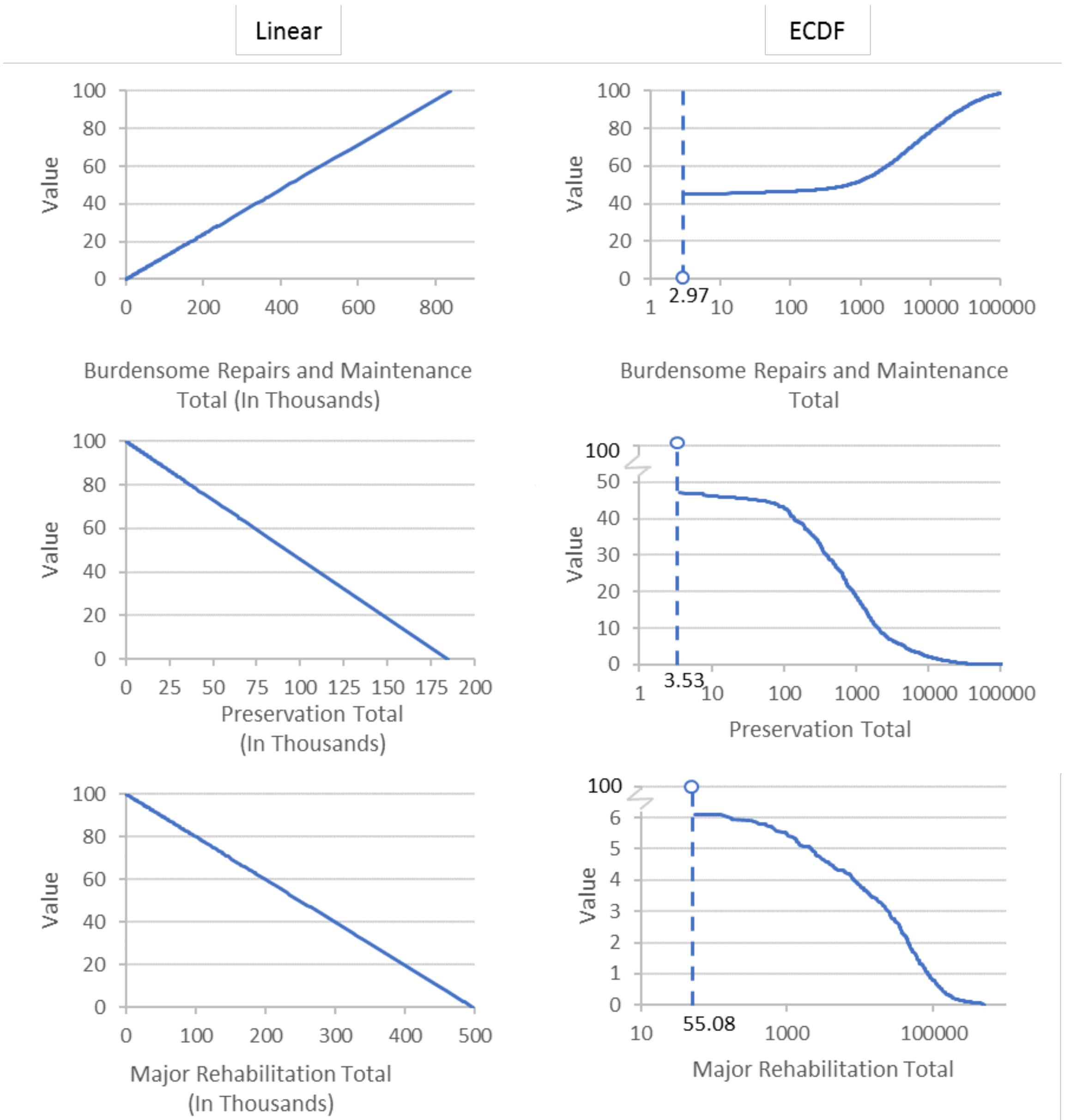


Figure B.6. Linear and ECDF Value Functions for Maintenance Burden

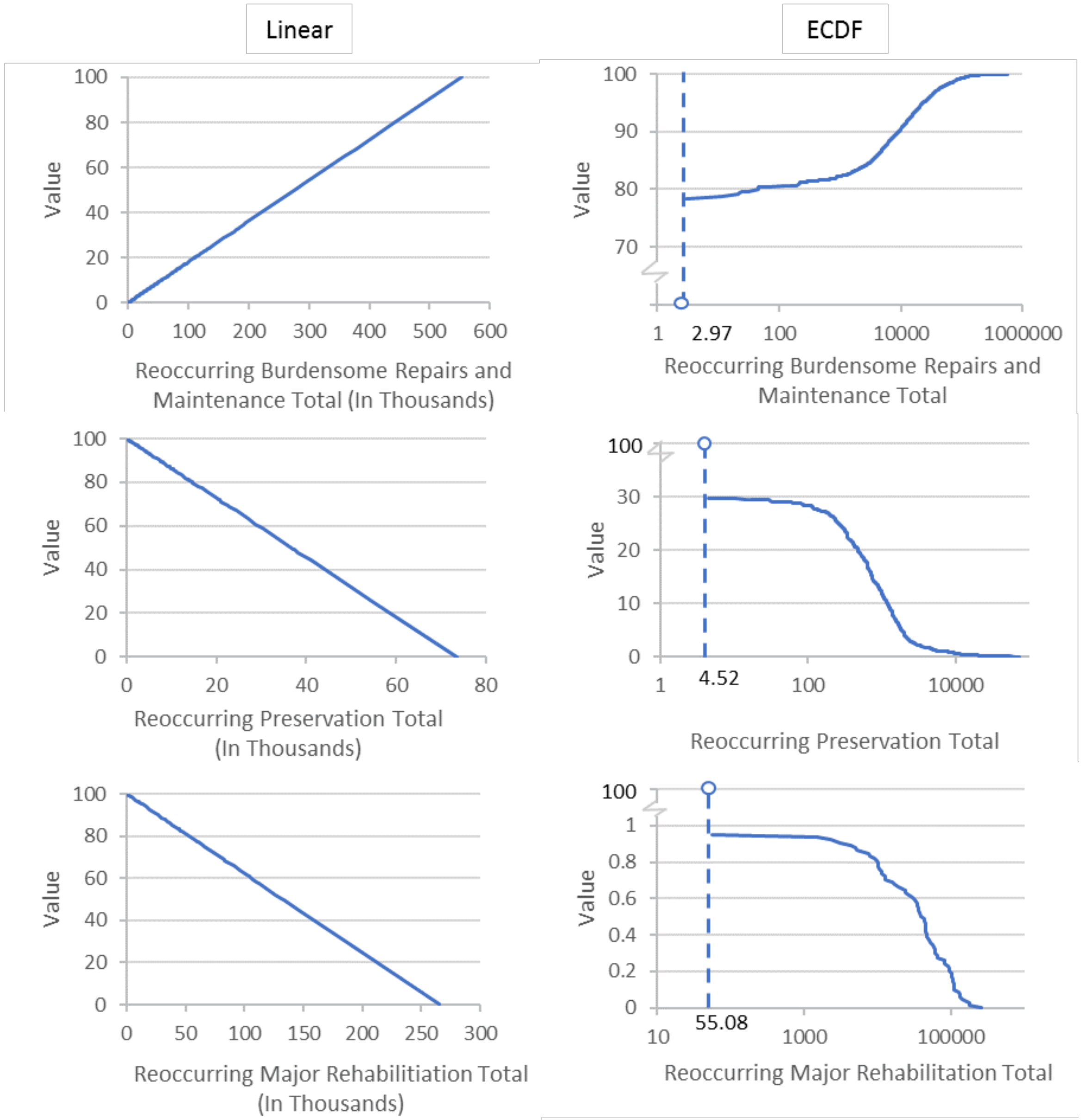


Figure B.7. Linear and ECDF Value Functions for Reoccurring Maintenance Burden

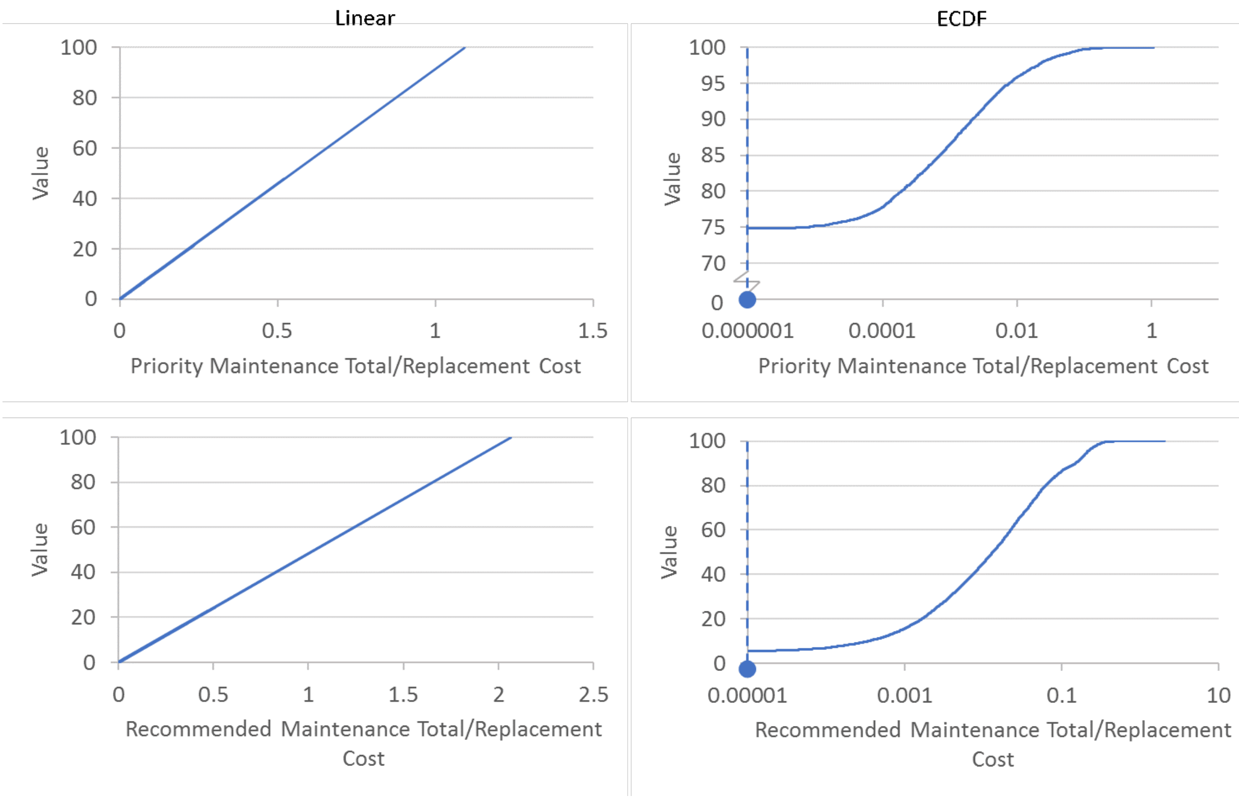


Figure B.8. Linear and ECDF Value Functions for Maintenance Needs Computed Relative to Estimated Replacement Cost

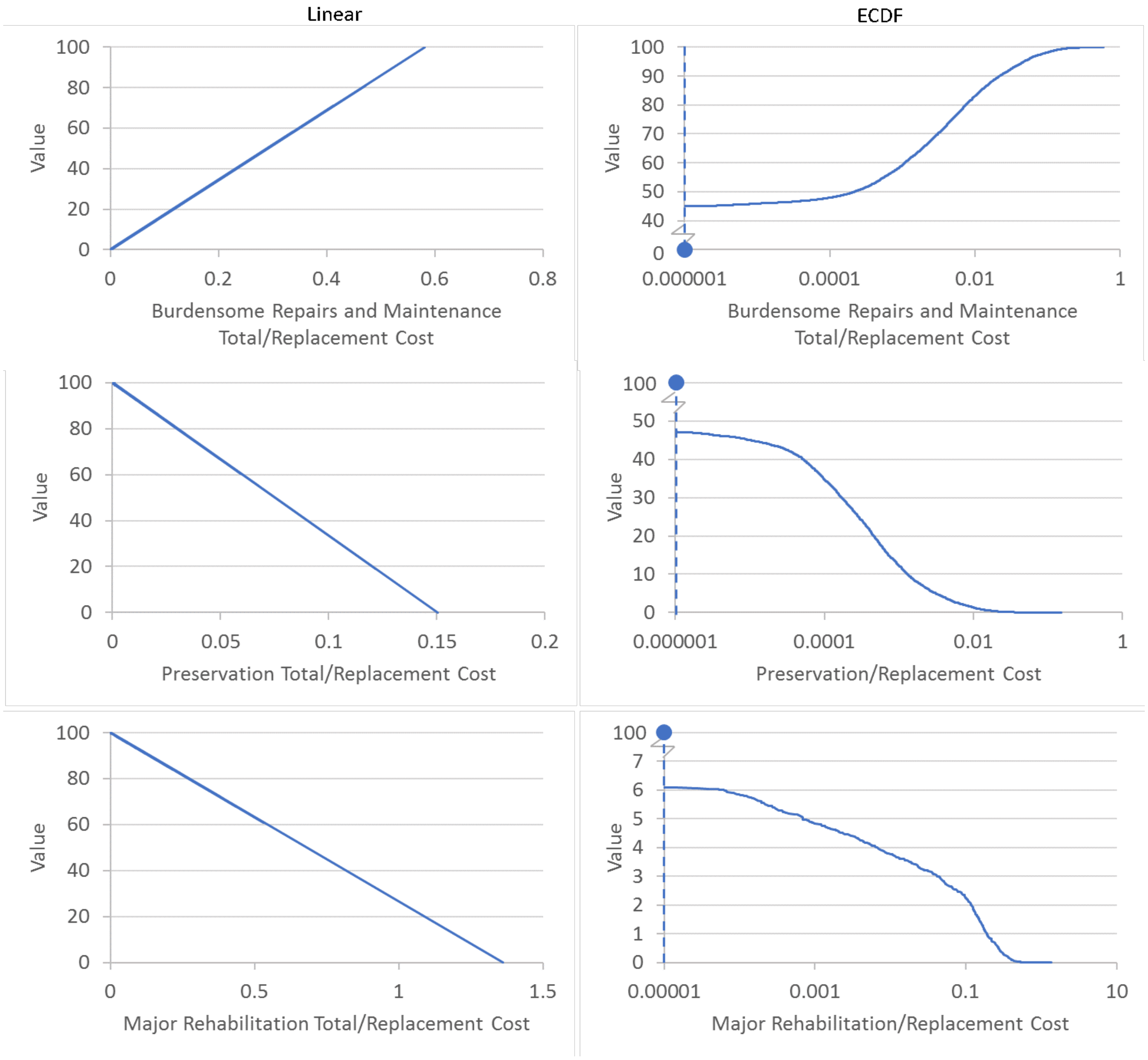


Figure B.9. Linear and ECDF Value Functions for Maintenance Burden Computed Relative to Estimated Replacement Cost

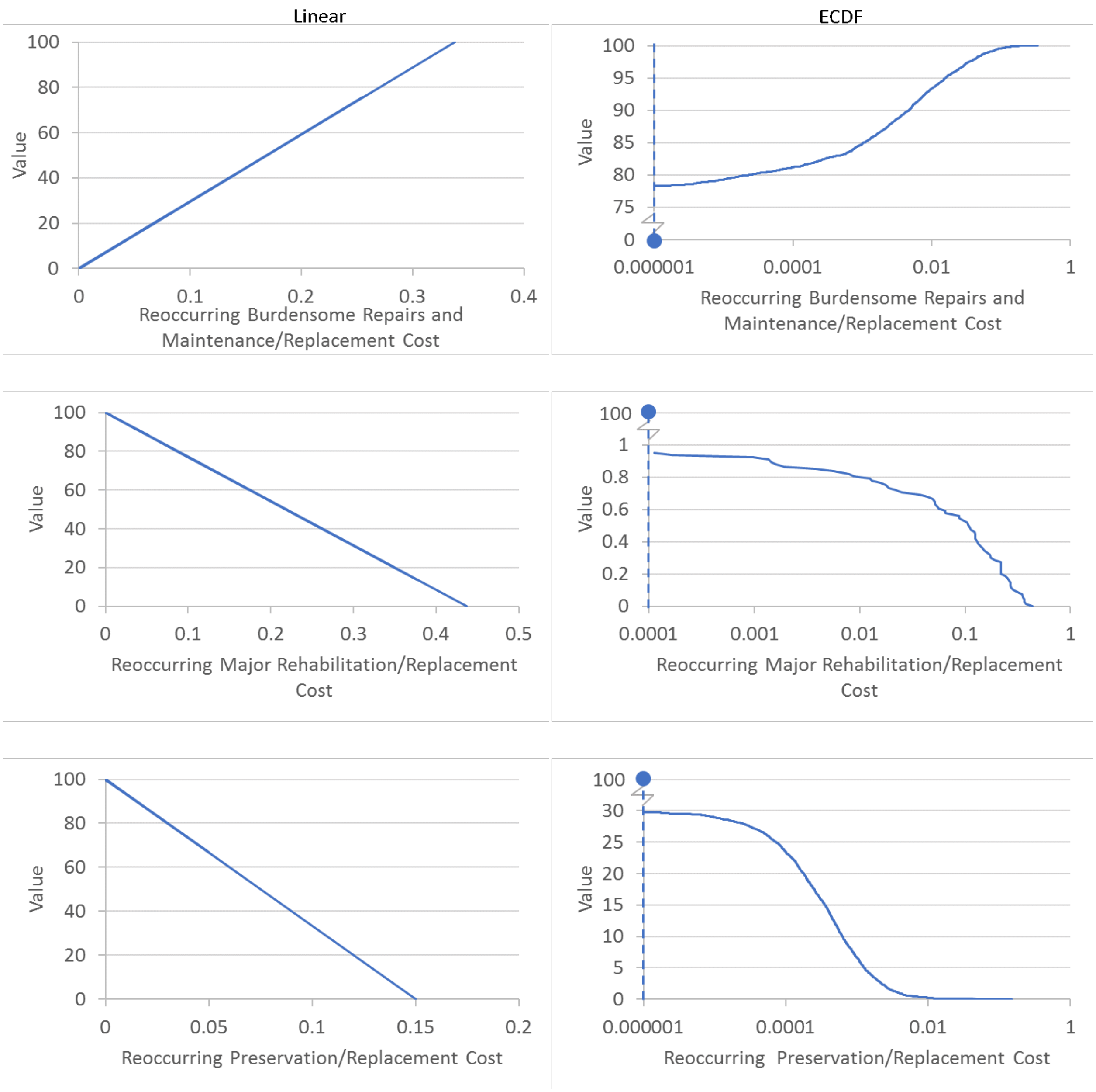


Figure B.10. Linear and ECDF Value Functions for Reoccurring Maintenance Burden Computed Relative to Estimated Replacement Cost