PERFORMANCE CRITERIA AND MEASURES
FOR PRIORITIZATION OF BRIDGE REPLACEMENT PROJECTS

by

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ABSTRACT

KELSEY M LANE. Performance criteria and measures for prioritization of bridge replacement projects. (Under the direction of DR. TARA L. CAVALLINE)

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 state highway agency (SHA) achieve performance criteria. Federal and state legislation provide guidance for national and statewide goals for transportation improvements, but SHA's are tasked with establishing prioritization indexes to measure progress towards those goals in a manner that reflects agency preferences and risk attitudes.

This thesis presents a portion of work required to support development of new prioritization indexes for bridge replacement, rehabilitation and preservation for the North Carolina Department of Transportation (NCDOT). To develop a list of proposed performance criteria and measures for bridge replacement, a review of published literature and a scan of SHA practices in the United States was performed to identify performance criteria and measures utilized by other agencies. The current prioritization index used by NCDOT, the Priority Replacement Index (PRI) was assessed to determine the current characteristics influencing this index, and to assess whether the current measures adequately meet legislative requirements and reflect agency preferences. An analysis of maintenance burden and maintenance needs data was performed to identify the best means of incorporating maintenance needs and maintenance burden into the prioritization criteria and measures and to justify their use.

The current PRI is most significantly influenced by measures of average daily traffic, bridge condition, and some measures related indirectly to safety. Several characteristics included in the current PRI are essentially double-counted, while other characteristics that could be linked to current federal and state goals do not appear in the current PRI. Analysis indicated that both maintenance burden and maintenance needs are significantly linked to bridges previously prioritized by NCDOT, and are therefore performance criteria that should be used in the new prioritization index for bridge replacement. A new set of performance criteria that more adequately reflects federal and state goals is recommended to NCDOT for consideration. Finally, a survey has been developed that can be utilized by NCDOT to determine relative weightings of these proposed performance criteria and measures.

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ABBREVATIONS

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
BPEG	Bridge Preservation Expert Task Group
Caltrans	California Department of Transportation
CEF	Cost effectiveness factor
CG	Capacity goal
CI	Consistency Index
CP	Single vehicle capacity priority
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
LP	Estimated remaining life priority
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
P4.0	Prioritization 4.0
PCI	Pavement condition index
PPN	Pavement priority number
PRI	Priority Replacement Index
RI	Random consistency index
ROPs	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	VermontAgency of Transportation
WP	Clear bridge deck width priority

CHAPTER 1: INTRODUCTION

1.1 Introduction

State highway agencies (SHA) are tasked with maintaining, repairing, and replacing bridges to support the travelling public. According to the U.S. Government Accountability Office, 14 of 24 state DOTs interviewed raised concern about the lack of adequate funding needed to meet the continually accumulating bridge maintenance needs (GAO, 2016). Faced with an aging infrastructure, increasing traffic, and less than optimal financial conditions, it is necessary for these agencies 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 budget 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 state agency achieve prioritization criteria. Measures of the relative importance of project attributes and impacts should 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 state highway agency 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.

In 2012, the Federal Highway Administration (FHWA) established MAP-21 legislation that provides a new framework for United States (US) transportation policy and funding allocation (U.S. Department of Transportation, 2012). Although it provides flexibility for states to identify and select candidate projects, MAP-21 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.

In 2013, the General Assembly of North Carolina enacted House Bill 817, the Strategic Transportation Investments Law (also known as the STI) (N.C. Department of Transportation, 2015). 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 quantative 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 is 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, the North Carolina Department of Transportation (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.

The NCDOT has utilized several prioritization measures and methodologies for bridges over the past several decades. In an effort to conform to the new federal and state legislation, and to create a formula that better reflects the current need, a new method of prioritization is desired. According to personnel in NCDOT's Structures Management Unit, the Priority Replacement Index (PRI) currently utilized for ranking of bridges for project selection and programming does not produce desirable outcomes. Specifically, the candidate projects sorted by PRI do not align with projects identified by personnel. A main desire for the new PRI 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. Also, the new formula should consider 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).

To comply with the funding formula for all capital expenditures presented in the STI legislation, NCDOT currently utilizes a prioritization strategy to guide scoring of both highway and non-highway projects, for all six modes of transportation. Currently NCDOT utilizes criteria outlined in Prioritization 4.0 (P4.0), with bridge projects presented under P4.0 Highway Criteria. P4.0 Highway Criteria includes suggested performance criteria of congestion reduction, benefit-cost, safety, economic competitiveness, accessibility/connectivity, freight, multimodal, lane width, paved shoulder width, and pavement condition (N.C. Department of Transportation, 2015).

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. There is a need for NCDOT to utilize this optimization approach, along with the extensive data available in the NCDOT Agile Assets 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 590, a select set of performance criteria and performance measures most significant for bridge prioritization in North Carolina needs to be identified. 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. Value functions that mathematically allow data to be manipulated into meaningful quantitative indices need to be developed to allow bridges most urgently in need maintenance, repair, or replacement to be easily identified. Finally, the new prioritization index needs to be evaluated and calibrated using the extensive data available in the Agile Assets BMS and lists of previously prioritized bridge projects.

1.2 Research Significance

This thesis presents a portion of work required to support development of new prioritization indexes for bridge replacement, rehabilitation and preservation for NCDOT. Specifically, the work presented within this thesis focuses on the development of performance criteria and measures for prioritization of bridge replacement, and includes the following contributions:

- Results of a literature review and scan of United States SHAs for performance criteria and measures used to prioritize bridge replacement, rehabilitation, and preservation projects
- Breakdown and assessment of the current PRI utilized by NCDOT to prioritize bridge replacement, rehabilitation, and preservation projects.
- Assessment of maintenance burden and maintenance history data for use in the future prioritization index
- Identification of appropriate performance criteria and measures that move towards current legislative goals while balancing agency preferences and risk tolerances, and
- Development of a survey for determining relative weightings of performance criteria and measures.

1.3 Organization of Thesis

This thesis consists of seven chapters. Chapter 1 provides an overview of current issues and regulations regarding bridge prioritization methods, with a focus on establishing the need to develop new performance criteria and measures to be used in a new bridge prioritization process for the NCDOT. Chapter 2 is a literature review of current recommendations and practices for bridge prioritization methods and includes a nationwide scan of current SHA practices for bridge prioritization. Chapter 3 focuses on North Carolina's current priority replacement index (PRI) for bridge prioritization and examines how individual characteristics influence the current PRI, along with identifying areas of redundancy, bounds, and situation dependent factors. Chapter 4 presents an analysis of NCDOT's bridge maintenance burden and maintenance needs data, identifying maintenance actions and needs linked to bridges recently prioritized for replacement. Building upon information presented in Chapters 2 through 4, recommended performance criteria and measures for a new bridge project prioritization index for NCDOT are presented in Chapter 5. In Chapter 6, a proposed survey to facilitate determination of the relative weighting of the performance criteria and measures for risk and preference is presented. The recommended approach for the survey process and analysis of the survey results is provided. Chapter 7 provides this work's conclusions, and provides recommendations for future work. Appendix A includes additional tables and figures to support maintenance burden and maintenance needs analysis presented in Chapter 4. Appendix B includes full copies of the initial and final survey for the relative weighting of the performance criteria and measures, presented in Chapter 6

CHAPTER 2: LITERATURE REVIEW

2.1 Overview of Bridge Management Systems

Each year, the FHWA acquires bridge data for the National Bridge Inventory database. From this information, the state of the National Network of Highway Bridges can be assessed and tracked over time. Currently, of the 609,539 bridges in the United States, 58,495, or 9.6%, are considered structurally deficient (Cardno, 2016). Each SHA or Department of Transportations (DOTs) spends millions of dollars each year repairing, replacing, and maintaining existing infrastructure (AASHTO, 2008). 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 data and to aid in prioritizing bridges for maintenance, repair and replacement. 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 management system not only leads to maintenance that keeps bridges in good condition, but also increases their service life (Hearn et al. 2013). Currently, there are a number of BMS used throughout the world. For example, AASHTO BMS is the most widely used in the U.S., OBMS in Ontario, the Finnish BMS, DANBRO in Denmark, and a BMS for the administrative divisions of Japan (Akgul, 2015).

Due 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 had to 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 what type of action needs to take place to ensure good condition and safety to the public. In 1987, research led by Dr. David Johnston at North Carolina State University (NCSU) helped North Carolina create one of the first BMS in the United States (Chen and Johnston 1987). Since this time, the North Carolina 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. 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 maintenance, repair, and rehabilitation (MR&R) options to achieve a desired level of service is still needed, and work presented within this thesis is part of this effort.

2.2 Decision-Making in Project Prioritization

Prioritization methods provide a framework for SHA to select bridges for MR&R. 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 done, for example when the preferred order is based purely on cost. Other times, the situation is more complex and there are multiple factors affecting the ranking and there can be conflicting criteria. Decision makers are often faced with the process of value trade off, which is when the he or she must choose between the benefits derived from of one criterion relative to another (Patidar et al. 2007).

2.2.1. Selection of Performance Criteria and Performance Measures

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). Keeny and Raiffa (1976) indicate that performance measures should satisfy the following criteria:

- 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.

Performance criteria and performance measures currently utilized by NCDOT for prioritization of many projects are described in Prioritization 4.0. Designed to meet the requirements of North Carolina’s Strategic Transportation Investment (STI) legislation (House Bill 817, June 26, 2013), P4.0 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, 2015). The STI funds are allocated towards Statewide Mobility (40%), Regional Impact (30%), and Division Needs (30%). P4.0 provides a framework for funding allocation for highway, non-highway, aviation, bicycle/pedestrian, ferry, and rail mobility projects. It is noted that Section 136-189.11(c) of the STI legislation specifically excludes bridge projects from the criteria used to rank other projects (by Strategic Mobility, Regional Impact, and Division Need). Although bridges are exempted from STI prioritization criteria, it is the desire of NCDOT Bridge Management personnel to comply with the spirit of this prioritization methodology, and the research project associated with this thesis work is an effort in that direction.

The P4.0 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 (Table 2.2). 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.

Table 2.1: NCDOT P4.0 highway performance measure weighting (NCDOT, 2015)

Performance Criteria	**Performance Measure**	**Measure Weight**
Congestion	Volume / Capacity	60% (Statewide)
		80% (Regional)
		100% (Division)
	Volume	40% (Statewide)
		20% (Regional)
		0% (Division)
Benefit-Cost	Benefit-Cost	100%
Safety	Crash Density	33%
	Crash Severity	33%
	Critical Crash Rate	33%
	Crash Frequency	50%
	Severity Index	50%
Economic Competitiveness	% Change in Value Added	50%
	Long-term Jobs	50%
Accessibility / Connectivity	County Economic Indicator	50%
	Upgrade Roadway Travel Time Savings	50%
Freight	Truck Volume	50%
	Volume / Capacity	30%
	Distance to Freight Terminal	20%
Multimodal	Distance to Multimodal Passenger Terminal	60%
	Volume / Capacity on Route near Multimodal Passenger Terminal	40%
Lane Width	Lane Width Difference	100%
Paved Shoulder Width	Paved Shoulder Width Difference	100%
Pavement Condition	Pavement Condition Rating	100%

Table 2.2: NCDOT P4.0 highway performance criteria weighting (NCDOT, 2015)

Funding Category	Quantitative Data	Local Input	
		Division Rank	MPO/RPO Rank
Statewide Mobility	Congestion = 30% Benefit-Cost = 25% Safety = 15% Economic Competitiveness = 10% Freight Mobility = 15% Multimodal = 5%	--	--
	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%		

As seen above in Table 2.2, 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 2.1 and Table 2.2:

$$\text{Division Needs} = 0.25\ (\text{Division Rank}) + 0.25\ (\text{MPO / RPO Rank}) + 0.50\ (\text{Quantitative Data}) \tag{2.1}$$

where:

$$\text{Quantitative Data} = 0.15\ (\text{Congestion}) + 0.15\ (\text{Benefit-Cost}) + 0.10\ (\text{Safety}) + 0.05\ (\text{Accessibility / Connectivity}) + 0.05\ (\text{Freight}) \tag{2.2}$$

$$\text{Congestion} = 1.00\ (\text{Volume / Capacity}) \tag{2.3}$$

$$\text{Benefit-Cost} = 1.00\,(\text{Benefit - Cost}) \tag{2.4}$$

$$\text{Safety} = 0.33\,(\text{Crash Density}) + 0.33\,(\text{Crash Severity}) + 0.33\,(\text{Critical Crash Rate}) + 0.50\,(\text{Crash Frequency}) + 0.50\,(\text{Severity Index}) \tag{2.5}$$

2.2.2 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 2.1.

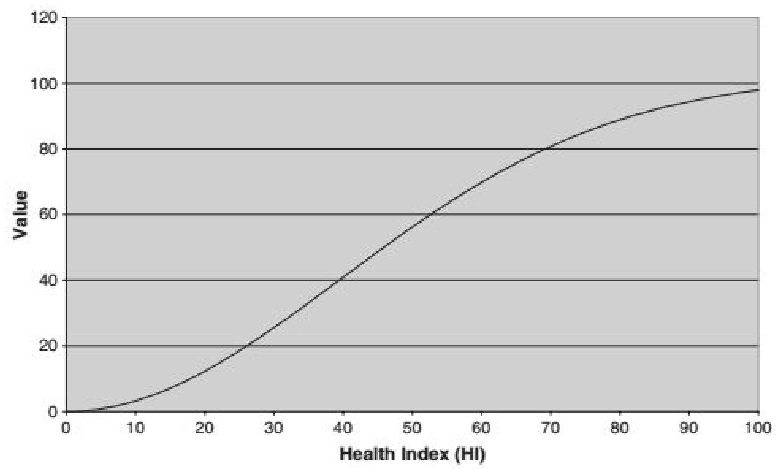


Figure 2.1: Example value function (from Patidar el al. 2007)

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

$$v\ (z) = v\ (\ z_1, z_2, \ldots\ldots , z_n) \tag{2.6}$$

where: v = value function

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

If two alternatives exist (alternative A and alternative B), each defined by a set of measures $\{z\}$, function (2.7) below, can be used to address the trade-offs among multiple criteria, or sets of measures:

$$v(\{z\}^A) > v(\{z\}^B) \tag{2.7}$$

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):

$$v\,(z_1, z_2, \ldots\ldots, z_p) = \sum_{i=1}^{n} v_1(z_i) \qquad (2.8)$$

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:

$$Ku(z_1, z_2, \ldots z_p) + 1 = \prod_{i=1}^{n} [\, kk_i u_i(z_i) + 1] \qquad (2.9)$$

where: u_i = single criterion utility function over the criterion z_i

k *and* k_i= scaling constants

2.2.2.1 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.

2.2.3 Survey Techniques to Establish Relative Weighting of Performance Criteria

The value functions represent the preference within each performance measure, but do not compare the criteria to one another. To determine which criterion has more influence than another's, the relative weight of each 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. Researcher Panos Parlos (2000) lays out three steps for how to utilize any decision-making technique:

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.

2.2.3.1 Direct Weighting

Direct weighing 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; ODOT, 2003, SDDOT, 2016).

2.2.3.3 Analytical Hierarchy Process (AHP)

The analytical hierarchy process (AHP) is based on the expertise of T.L. Saaty, who found a way to develop an easy-to-implement methodology for complex decision making (Bhushan and Kanwal, 2004). A decision can only be made when the problem, purpose, criteria, and stakeholders are known. According to Saaty, there are only two ways to solve a problem, either by studying and examining it itself to all extents or by studying the problem by comparing it to similar problems (Saaty, 2008). 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 Kanwal, 2004).

The fundamental framework of the AHP by T.L. Saaty 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 2.2).
3) Construct pairwise comparisons matrices.
4) Use the priorities obtained from the comparison to weigh the priorities in the level immediately below them. Add all the weight values together to obtain the overall priority.

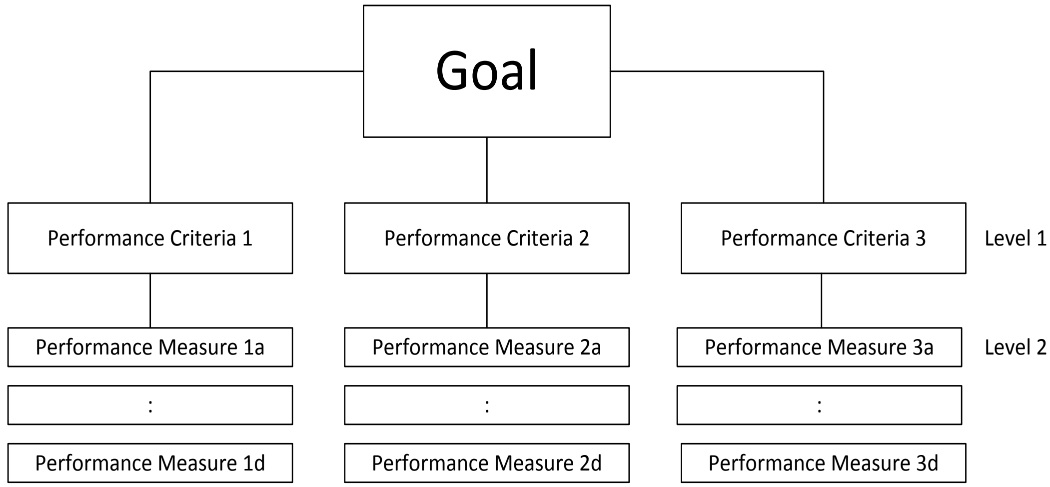


Figure 2.2: Generic hierarchic structure (Saaty, 2008)

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 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):

$$A = \begin{pmatrix} 1 & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ 1/a_{1n} & \cdots & 1 \end{pmatrix} \tag{2.10}$$

where: *A* = comparison matrix

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

$$w_i = \frac{1}{n}\sum_{j=1}^{n} a_{ij}w_j \text{ (for } i = 1,2,\ldots.n\text{)} \tag{2.11}$$

where: *w = weight*

2.2.3.3.1 Treatment of the AHP Scale of Importance

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 2.3: 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 2.4. Another variation appears in the NCHRP Report 590, shown in Table 2.5, 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 2.4: 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 2.5: 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

2.2.3.3.2 Survey Process

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 2.6). 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 2.6: 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		

2.2.3.3.3 AHP Checking

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:

$$CI = (\lambda_{max} - n) / (n - 1) \qquad (2.12)$$

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 2.7) to determine the consistency ratio.

$$CR = CI / RI \tag{2.13}$$

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 2.7: 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

2.2.3.3.4 Combing Survey Results Obtained from a Group of Participants

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 2.8. 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 2.8: 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

2.2.3.3.5 Examples of the Use of AHP

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).

2.2.3.4 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).

2.3 Bridge Project Prioritization in North Carolina

The purpose of this work is to identify performance criteria and measures for prioritization of bridge replacement for NCDOT. In the following sections, a brief history of bridge project prioritization in North Carolina is provided. A summary of the current bridge prioritization index, the Priority Replacement Index (PRI) is presented, with additional information on this index provided in Chapter 3. Recent legislative requirements are discussed, with a focus on their impact on the criteria and measures currently used by NCDOT for bridge project prioritization.

2.3.1 History of Bridge Project Prioritization in North Carolina

Over the years, the North Carolina Department of Transportation (NCDOT) has used various methods to guide bridge project prioritization and selection. According to NCDOT personnel, the method used prior to 1990 was simply 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 list of 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 of why a specific 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. This program, called OPBRIDGE, ran on the NCDOT mainframe. 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" candidates to be compared with the top candidate bridges from the other divisions. In order to optimize the list, each candidate was entered into the system twice. The first run was based only on the priorities given from the division, the second only considered all non-scheduled bridges. A final list was then sorted by Deficiency Points and sent to a committee for review and selection of the rehabilitation and replacement projects. If additional funds were available, they would utilize the statewide OPBRIDGE optimization program to help identify additional candidate bridges. The final list would then be reviewed and programmed into the Transportation Improvement Program (TIP) (Garrett, 2012).

Beginning in 2012, two key changes were made to the 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 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. NCDOT personnel were not satisfied with the correlation of Deficiency Points scoring to the PRI. As discussed previously (and will be established in Chapter 3 of this thesis), 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 current process for bridge project prioritization uses the PRI formula. Each year, once the PRI for each bridge is produced, a top priority candidate list is created, and the committee-based project selection process described above is repeated (Garrett, 2012). Currently, the NCDOT Agile Assets BMS does not directly identify the project selections based on the PRI. Currently, bridges prioritized based on the PRI score do not adequately reflect NCDOT preferences, spurring the need for the research effort supporting this thesis and related work (Whelan and Cavalline, 2015).

2.3.2 Priority Replacement Index (PRI)

North Carolina currently uses the Priority Replacement Index (PRI) to determine prioritization for bridge maintenance, repair, and replacement projects. As stated above this prioritization index was initially utilized during 2012. The PRI consists of three main components: Deficiency Points, Sufficiency Rating, and Structural & Functionality (which considers the deck, superstructure, and substructure ratings). Additionally, 10 points are allocated if the bridge is currently utilizing temporary shoring. The formula for the PRI is shown in Equation 2.33 (Garrett, 2012):

$$0.45(Deficiency\ Points) + 0.45(100 - Sufficiency\ Rating) + 1.25[28 – (DK + SP + 2SB) + 10\ if\ temporary\ shored \quad (2.14)$$

where: *DK* = Deck Rating

SP = Superstructure Rating

SB = Substructure Rating

For a given bridge, the PRI can be a maximum of 120 points. Priority is given to bridges with higher PRI scores. Deficiency Points are calculated on a scale of 0 to 100 and comprise 37.5% of the PRI. The Sufficiency Rating (SR) is also on a 0 to 100 scale and comprises 37.5% of the total PRI. The Structural and Functionality Rating are on a 0 to 20 scale and comprise 16.6% of the PRI. Lastly, if a bridge has temporary shoring, 10 points are added to the PRI, comprising 8.3% of the PRI. Computation of each of these components utilizes a set of inputs comprised of data available in the NCDOT BMS (Garrett, 2012).

To compute each component of the PRI, a number of performance measures are utilized with sometimes complex, non-linear functions used to assign scores. A more complete discussion of the PRI, including a breakdown of each component, is provided in Chapter 3. 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 may exist, as well as underrepresented factors of interest to NCDOT and over-represented metrics that skew the index.

2.3.3 Recent Legislative Requirements

Over recent years, both Federal and State Legislation for bridge prioritization and funding has changed to reflect the national and state goals for highway systems. MAP-21 is the most recent Federal legislation in which each state must follow to obtain funding for both existing and future bridge infrastructure. An overview of this Federal Legislation, as well as the approaches utilized by a variety of SHAs to determine how to direct project funding, is presented in this section.

2.3.3.1 Federal Legislation

The MAP-21 legislation places emphasis on performance-based funding of transportation projects at the program level. MAP-21 legislation is currently guiding development and modification of methodologies utilized to inform funding decisions of many state highway agencies. Performance-based funding requires states to utilize performance measures to aid project prioritization and selection at the system level. MAP-21 identifies seven national goals: safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and project delivery, and relies on the judgement of state highway agency personnel to develop specific goals, measures, and targets to assess progress towards these goals (U.S. Department of Transportation, 2012).

2.3.3.2 Other States Approach to Legislative Requirements

Bridge funding programs are structured differently in each state, and MAP-21 requirements facilitate state flexibility in determining how to direct project funding. At the current time, a wide variety of strategies for funding allocation exist among the states. 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).

2.3.3.3 North Carolina Legislation

North Carolina ratified the Strategic Transportation Investment (STI) legislation (House Bill 817) in order to comply with the new legislation of MAP-21. Signed by Governor McCrory in June 2013, it established a strategic prioritization funding plan for the State's transportation resources. It mandates an investment formula with an objective ranking framework to prioritize and justify construction, maintenance, and preservation projects. 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 2.3.

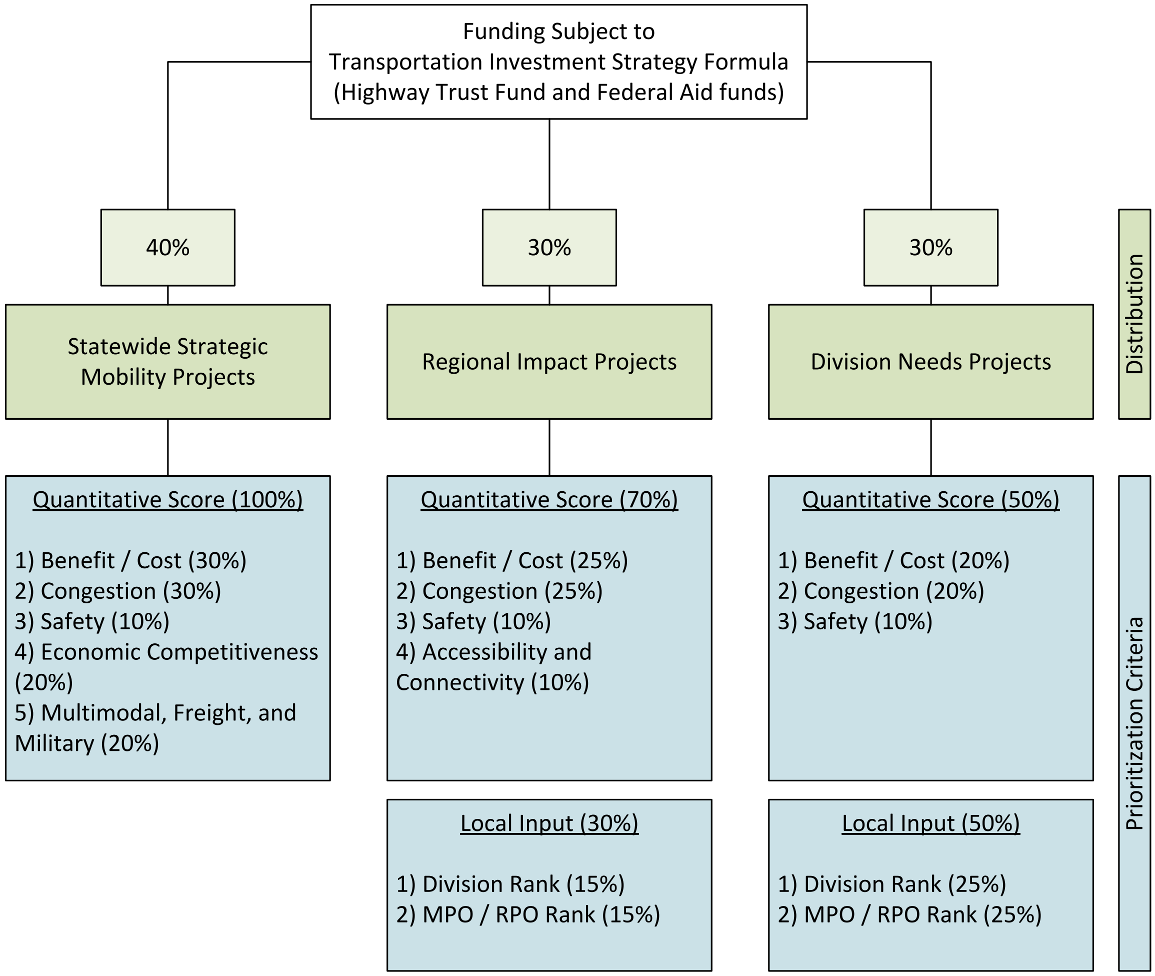


Figure 2.3: Overview of Strategic Transportation Investment prioritization funding plan with 2013 criteria proposed by Board of Transportation for Highway projects

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 quantitative 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 4.0 (or P4.0) to allocate funds for transportation projects subject to the STI, including aviation, bicycle/pedestrian, ferries, highways, public transportation and Rail (NCDOT, 2015). Additional information on NCDOT's P4.0 is presented in subsequent sections, as applicable to specific bridge prioritization strategies. It is noted that bridges are specifically exempted from STI prioritization requirements. However, NCDOT Bridge Management personnel have expressed a desire to demonstrate similar objective and transparent prioritization criteria for selection of bridge projects.

2.4 Prioritization of Bridge Projects

Transportation departments need to maintain thousands of bridges, each varying in age and in need of different maintenance, repair, and rehabilitation (MR&R). To help allocate resources, transportation departments need to choose which bridges will get repaired or replaced each year. To select bridges for funding, each transportation department must prioritize potential bridge projects to ensure that the appropriate bridges get the attention they need. For example, in California, the DOT (Caltrans) has a goal of only 5% of all bridges below an 80 on the states Bridge Health Index score. Therefore, Caltrans has developed a system in which the main objective is to maintain the condition of the structure, using the health index to aid in identifying the needed preservation action (Shepard and Johnson, 2001).

2.4.1 NCHRP Report 590 Recommended Methodology for Bridge Project Prioritization

Due to aging infrastructure, increased traffic, decreased resources, and more complex demands on our highway system, more complex challenges are being faced by SHA. NCHRP was developed to fund research that finds the most modern scientific techniques that can be used by SHA for highway management. 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. At the time of the initiation of the study, many states did not utilize optimization algorithms within their BMS to select projects. Methods used in the past that only made prioritization decision based on lowest cost usually had unsatisfactory results. Agencies expressed the need for the system to include decision making methodologies such as: "bridge condition, safety, traffic flow disruption, and vulnerability" (Patidar et al. 2007). In NCHRP Report 590, 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*

In addition to these performance criteria, NCHRP provides guidance to facilitate the inclusion of preference and risk for decisions involving multiple performance criteria and measures. In this report, the process of utility theory is presented, which is recommended due to its ability to allow for the decision makers' preference to be mathematically represented. The utility theory has three major parts: weighting, scaling, and amalgamation. This process can be applied to both bridge level and network level (Patidar et al. 2007).

2.4.2 Bridge Project Prioritization Strategies Currently Utilized in Other States

The NCHRP Report 590 presents clear, well defined guidance for states to enhance their bridge prioritization strategies. Many states have adapted methodology from Report 590, or have a different prioritization model that is specific to their individual state needs. As outlined previously, new MAP-21 federal regulation calls for each state to have a prioritization method that includes defined performance criteria and performance measures to be eligible for federal funding (U.S. Department of Transportation, 2012). Although each state has a particular way of prioritizing bridges projects, prioritization methods vary based on states preferences, BMS capabilities, and other factors. In the following paragraphs, an overview of available literature (on state practices) is presented.

The identification of performance criteria and measures that reflect a SHA's preferences while meeting legislative requirements is key to establishing bridge project prioritization strategies. 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 2.9. Based upon these findings, Hearn et al. 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 2.9: 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 et al. 1991, Sinha and Labi 2007, Li and Sinha 2009). Performance goals and measures utilized in the Indiana BMS are presented in Table 2.10.

Recently, Li and Sinha (2009) performed a study to determine relative weights of goals and performance measures. The AHP process was utilized to analyze survey data collected via the Delphi method 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 2.10: 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 2.4) 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 2.5), which are made up of specific performance measures to determine which bridge is of greatest priority.

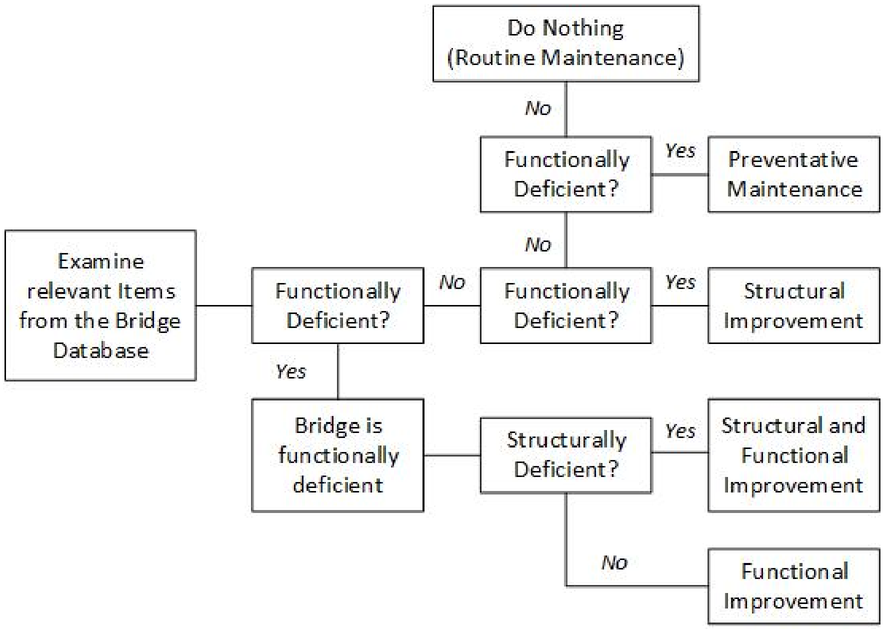


Figure 2.4: DTREE (Sinha et al. 2009)

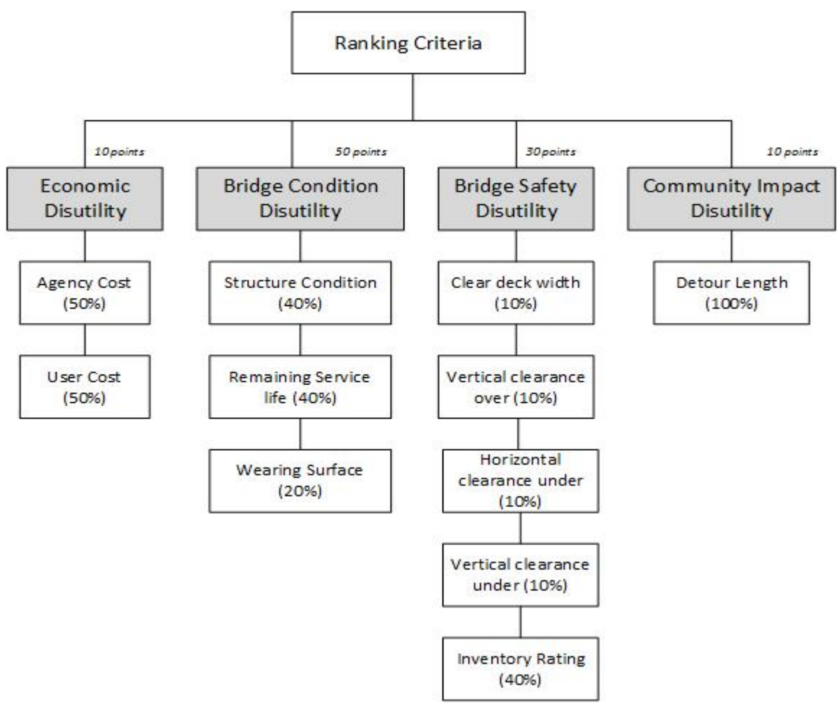


Figure 2.5: Rank system (Sinha et al. 2009)

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 2.11. 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 2.15:

Table 2.11: 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)

$$U_t = a_1\beta_1X_1 + a_2\beta_2X_2 + a_3\beta_3X_3 + a_4\beta_4X_4 + a_5\beta_5X_5 \quad (2.15)$$

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:

$$X_i = 1 / (1 + e^{-C_i}) \tag{2.16}$$

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 2.12 shows of the C for each value component is determined:

Table 2.12: 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 2.13 shows the results of those weights for each component. As seen in this table, rehabilitation and replacement needs account for 25 percent of the total rating for bridge prioritization (Johnson, 2008).

Table 2.13: 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 2.14:

Table 2.14: 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

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).

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 follows (Ohio DOT, 2003):

Table 2.15: 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

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 2.16: 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 2.17, similar to Ohio DOT, New Jersey DOT, Colorado DOT, and California DOT (SDDOT, 2015).

Table 2.17: 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 presented.

2.4.2.1 Infrastructure Condition

One of the most commonly utilized performance criterion used by SHAs for bridge project prioritization is bridge condition. As shown in Table 2.9, 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, sufficiency rating, etc (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 coined this index the California Health Index. This Health Index is computed as follows:

$$HI = \left(\frac{\sum CEV}{\sum \text{TEV}}\right) \times 100\%$$

$$TEV = TEQ \times W$$

$$CEV = W \times \sum(QCS \times WF)$$

$$WF = 1 - \frac{i-1}{State\ Count-1} \qquad (2.17)$$

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 is “used by federal and state agencies to determine the relative sufficiencies of all of the nation’s bridges (NBIS, 2012),” and eligibility for federal funding for bridge projects has been dependent on sufficiency rating score. The sufficiency rating incorporates four factors to determine a final numerical score. If the final score is higher, it indicates that the bridge is good, 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 (Federal Highway Administration, 1995):

$$SR = S_1 + S_2 + S_3 + S_4 \tag{2.18}$$

Where the four factors are as follows (Federal Highway Administration, 1995):

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 uses a single equation that uses a combination of three overarching performance measures to determine the bridge condition disutility, as shown in Equation 2.19. The formula includes the 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. The structural condition disutility function computed using the weighted sum formula shown in Equation 2.19 (Sinha et al. 2009). This approach used by Indiana is unique in that it uses decision analysis to incorporate preference and risk into the disutility function.

$$U_{COND} = w_{SCR}U_{SCR} + w_{RSL}U_{RSL} + w_{WSCR}U_{WSCR} \quad (2.19)$$

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 compute priority on a scale with 100 points, with bridge condition being worth up to 60 points of the total 100. Bridge condition is broken down into eight performance measures (SDDOT, 2016):

a) Posting (29 max points) - As defined by NBI Item 70

Table 2.18: 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 2.19.

c) Superstructure Condition (6 points max) – As defined by NBI Item 59, with ranking points assigned as shown in Table 2.19.

Table 2.19: Condition rating (SDDOT, 2016)

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

d) Culvert Condition (12 points max) – As defined by the NBI Item 62, with ranking points assigned as shown in Table 2.19.

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:

$$(1 \text{ point max}) - (100 \times SR) / 100 \tag{2.20}$$

One of the simplest bridge condition formula was developed by the Oregon Department of Transportation. It address 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 (presented in Section 2.4.3.1), 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):

$$\text{Points} = (100 - \text{Sufficiency Rating}) / 10 \tag{2.21}$$

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.

2.4.2.2 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 helps 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. For example, if a committee is looking to find which highway should be built first and they want to maximize net public benefits, then the benefit-cost ratio should be used. This would allow for each highway to be compared to one another and create an overall ranking (Dahlgren et al. 2004).

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 in project prioritization in different ways by different SHAs. 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):

$$\text{User Impact (On-System)} = \text{ADT} \times \text{Detour Length (miles)} / 350 \tag{2.22}$$

$$\text{User Impact (Off-System)} = \text{ADT} \times \text{Detour Length (miles)} / 100 \tag{2.23}$$

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 2.20: 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 2.25.

$$CEF = \frac{365 \times ADT \times BL \times Total\ Deck\ Width}{EUAC_{\infty}} \quad (2.24)$$

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 2.25. 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 2.26.

$$U_{UC} = EUAUC \text{ or } EUAC_{UC,\infty} \quad (2.25)$$

where: U_{UC} = user cost disutility

EUAUC = equivalent uniform annual user cost in perpetuity

$$U_{econ} = U_{AC} + U_{UC} \tag{2.26}$$

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 P4.0 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, 2015). It is scaled based on the raw ratio only (Benefit / Cost to NCDOT), and is essentially user costs divided by agency costs. Project costs include agency costs associated with construction, right-of-way, and utility costs, with adjustments to costs made to account for contribution of non-federal and/or non-state funds to the project. Project costs specifically do not include the extra percentage for local funds and tolls. Additional funds from local contributors and tolls can be added to the Scaled Benefit-Cost score, but it cannot exceed 100 (NCDOT, 2015).

2.4.2.3 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" (U.S. Department of Transportation, 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 value, 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. The following is the disutility value for safety objectives (Sinha et al. 2009):

$$U_{SAFTEY} = W_{CDW}U_{CDW} + W_{VC}U_{VC} + W_{HR}U_{HR} + W_{IR}U_{IR} \qquad (2.27)$$

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 in NCDOT SPOT Online (NCDOT, 2015). In the NCDOT P4.0, the safety performance criterion is identified by using crash information for a given highway. Crash density, crash severity, and critical crash rate are used in prioritization of roadway projects, each making up 33% of the measure rate for the safety criterion. The crash frequency and severity index are used in prioritization of highway intersection projects, with both accounting for 50% of the safety measure weight (NCDOT, 2015).

2.4.2.4 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 follows (Ohio DOT, 2003). New Jersey accounts for congestion by weighting specific performance measures by average daily traffic (Szary and Roda, 2014).

Table 2.21: 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 4.0, 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 ratios and existing volume as performance measures for both statewide mobility and regional impact, and only existing volume/capacity ratio for division needs (NCDOT, 2015). As stated previously, bridge projects are not subject to STI prioritization, and these measures do not directly apply.

2.4.2.5 Vulnerability

Vulnerability is not mentioned in MAP-21 federal guidelines, the STI legislation, or NCDOT P4.0. 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 main 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 2.6. To measure the likelihood, 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 2.22), users can assign risk for each vulnerability types. The vulnerability score is defined as:

$$\textit{Vulnerability Rating} = \textit{Likelihood Score} + \textit{Consequence Score} \tag{2.28}$$

where: *Consequence Score* = Failure Type Score + Exposure Score

Exposuree Score = Traffic Volume Score + Functional Classification Score

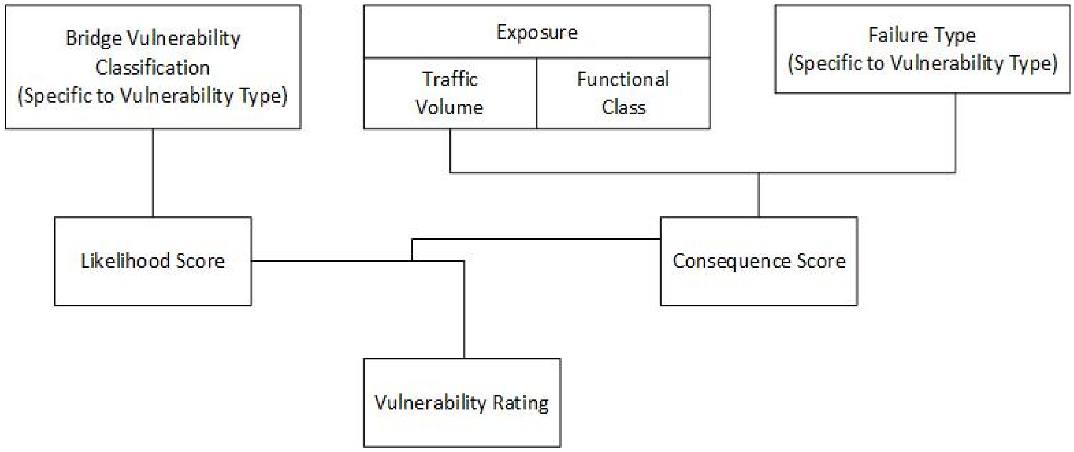


Figure 2.6: Vulnerability consideration (NYSDOT, 1996)

Table 2.22: 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

The score is converted to a rating between 1 and 5 associated with the following definitions shown in Table 2.23.

Table 2.23: 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 sections: 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 2.7 the representation of this process is graphically illustrated (Patidar et al. 2007).

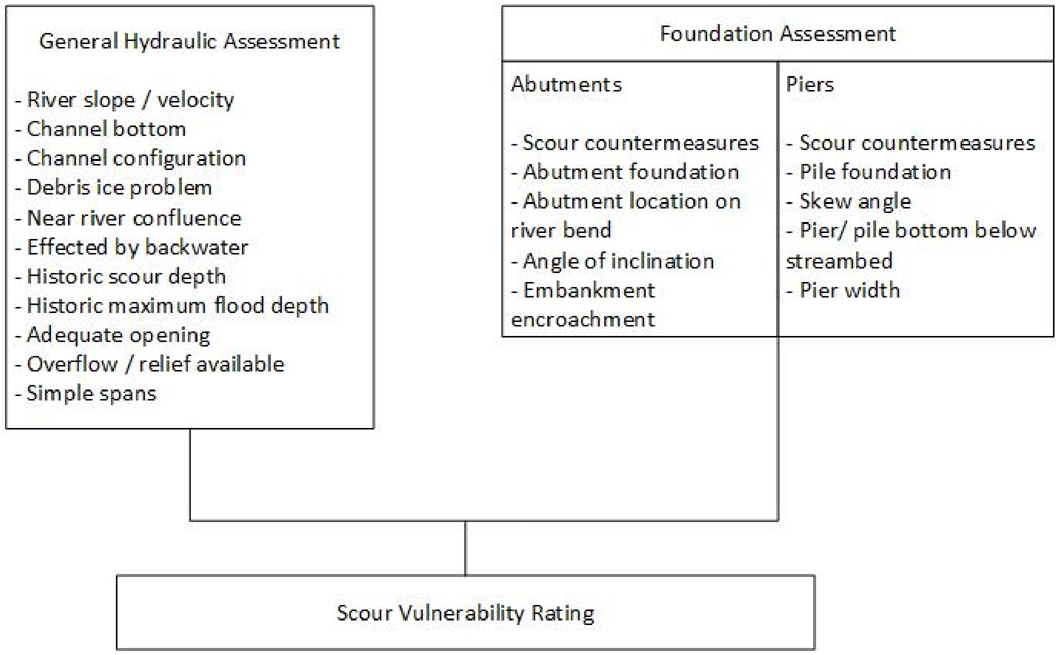


Figure 2.7: Scour vulnerability rating (Patidar et al. 2007)

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%. As a way to determine which bridges will receive prioritization, a main condition rating is used, as described in Section 2.4.3 but the condition rating is also combined with a risk assessment to determine a final weighted utility (Johnson, 2008). This helps determine if one bridge can provide more utility benefits over another. Table 2.21 shows a comparison of two bridges using this method (Johnson, 2008):

Table 2.24: 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 uses 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 2.30 (UDOT, 2014).

$$\text{Vulnerability Score} = 0.75(\text{BHI}) + \text{LRS} \qquad (2.29)$$

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 2.30 is used to determine its rating score (Bridge Management Manual, UDOT, 2014):

$$\text{LRS} = (\text{LR} - 0.3) / 0.028 \qquad (2.30)$$

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 2.22. 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 is used to help 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 2.25:

Table 2.25: 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

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 2.26) (UDOT, 2014).

Table 2.26: 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 following formula (Adams et al. 2014).

$$Combined\ Risk = \sqrt{Geo/HydraSafety^2 + Structural\ Safety^2 + Service\&Duribility^2 + Operations^2} \tag{2.31}$$

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 2.27) (Adams et al. 2014).

Table 2.27: 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

2.4.2.6 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 whose bridge project prioritization practices includes 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 2.25 (Ohio DOT, 2003):

Table 2.28: 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 P4.0, 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, 2015). Two performance measures are currently used for project subject to STI prioritization: percent change in county economy and long-term jobs created. The primary input is travel time savings, as computed using the TREDIS economic impact model, and the estimated increase of wages and productivity (NCDOT, 2015).

2.4.2.7 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 (Transportation Research Board, 2010). "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 (ODOT, 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 4.0 has a performance criterion for freight and includes three performance measures: truck volume, volume/ capacity on Non-Interstate STRAHNet or Future Interstate Route, and distance to freight terminal. Its purpose is to "measure the congestion along routes that provide connection to freight intermodal terminals and that have high truck volumes." This includes facilities within a 20 mile radius, which also includes major military bases (NCDOT, 2015).

NCDOT's P4.0 also considers the performance criterion of multimodal mobility under the category of statewide mobility. Its purpose is to assess bridge importance in a manner similar to the assessment of impact of a bridge on freight movement, but for routes with connections to multimodal passenger terminals. In Prioritization 4.0, multimodal mobility is addressed with two performance measures: distance to multimodal passenger terminal and volume/capacity on route near multimodal passenger terminal. The terminals need to be located within a 5 mile perimeter to qualify. These types of terminals include: Amtrak stations, major transit terminals, commercial service airports, red and blue general aviation airports, major military bases, and ferry terminals (NCDOT, 2015).

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.

2.4.2.8 Functionality

Functionality is defined by the geometric characteristics of a particular bridge. Neither MAP-21 nor Prioritization 4.0 include functional performance criteria. It is also not specifically mentioned in NCHRP Report 590's recommendations. However, 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 criterion 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. 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).

2.4.2.9 Maintenance

Performance criteria linked to maintenance are not specifically mentioned in MAP-21, the STI legislation, NCDOT P4.0, 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. 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 any 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 & 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).

2.5 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.

One key research need of NCDOT in an overall effort to enhance BMS capabilities is to revisit currently utilized performance criteria and measures for prioritization of bridge projects. These 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.

Additionally, steps to weight the new performance criteria and measures to adequately reflect the preferences and risk tolerances of NCDOT personnel will need to be identified and initiated. Work subsequently presented in this thesis partially addresses these research needs, identifying a proposed set of performance criteria and measures for consideration by NCDOT for future use in bridge prioritization, as well as a proposed framework and method for establishing weights for each of these metrics in the new bridge prioritization index currently in development.

CHAPTER 3: CURRENT PERFORMANCE CRITERIA AND MEASURES

3.1: Evaluation of Current Priority Replacement Index

As discussed in Chapter 2, North Carolina currently utilizes a composite score called the Priority Replacement Index (PRI) to aid in prioritizing bridge projects. The PRI consists of three main performance criteria, with related performance measures supporting assessment of each performance criterion. As part of this research work, an analysis of the PRI was conducted. The goal of this was to:

- investigate relative weighting of performance measures and prior indexes no longer used alone, but that continue to contribute to the PRI,
- identify potential sources of double-counting of criteria, and
- compare how well or how poorly these indexes reflect the performance criteria and relative weighting prescribed by the Strategic Transportation Investment Law for Statewide Strategic Mobility, Region Impact, and Division Needs projects.

3.1.2: Assumptions Required for Evaluation

Before examining the flow and inputs of the PRI formula, it is important to note several characteristics of the formula and its constituent components. Some performance measures used in each criterion are evaluated using linear equations, while some measures are nonlinear or are case dependent. Another characteristic is that there are bounds placed on the calculated results of most of the performance metrics used to compute components of the PRI. As a result of these nonlinearities, case-dependence, and point allocation boundaries, the exact contribution of individual characteristics to the PRI cannot be directly determined without first establishing some assumptions as a foundation of the evaluation.

As presented in Section 3.1.3, the contributions provided from each performance criteria and measure for the PRI have been established utilizing several simplifying approximations. In cases where a performance measure is case dependent, only the factors used in calculating the metric are incorporated, not the factor that defines the case dependency. For example, the calculation for Vertical Clearance Insufficiency metric used in S2 Serviceability and Functional Obsolescence in the sufficiency rating formula, the metric for determining the exact formula depends on if the bridge is on a route with a STRAHNET Highway Designation, and is computed using #53 Minimum Vertical Clearance Over Bridge Roadway. Both the sufficiency rating and the PRI are affected by both of the bridge characteristics in this instance, but the performance measure is primarily considering the minimum vertical clearance over the bridge roadway. Therefore, 100% of the Vertical Clearance Insufficiency metric is accounted for when attributed to #53 Minimum Vertical Clearance Over Bridge Roadway, while the field #100 which determines the case of the equation used was neglected.

Another challenge in determining the relative contribution of individual bridge characteristics occurs with the use of bounds. For example, within the Rating Reduction metric, S2: Minimum Vertical Clearance Over Bridge Roadway is used in the sufficiency rating formula. In this, the total number of points, 25, is developed from six fields, but the metric itself is bounded to 13 total points. Therefore, the formula is nonlinear and the contribution of each of the six fields is dependent on if the bound is exceeded or not. Each individual bridge characteristic was simplified to assume a relative contribution to the PRI for this research. In this particular instance, each of the six fields was computed to the relative percentage of the maximum point value that could be calculated without the use of bounds.

3.1.3 Influence of Bridge Characteristics on Performance Criteria

Based upon simplifying assumptions outlined in Section 3.1.2, the total contribution of each performance criteria and performance measure to the PRI was computed. To facilitate ease of presentation and explanation of this evaluation of the current PRI, the overall results of this evaluation are displayed (Figures 3.1 through 3.4, Table 3.1 and Table 3.2) as a reference to the reader while reviewing subsequent sections of this chapter. In Table 3.1, the maximum possible point contribution of each characteristic to the PRI is presented, while in Table 3.2 the decimal percentage contribution of each characteristic is presented. In Sections 3.1.3.1, 3.1.3.2, and 3.1.3.3, a detailed explanation of how the contribution of characteristics to each performance measure were computed is provided.

To both understand the contribution of each performance measure to the current PRI, a “tree” diagram was prepared, using a hierarchical structure and color to aid in showing relationships and influence of associated measures. Figures 3.1 through Figure 3.4 display how each performance criteria and performance measure feed into the PRI. The first diagram, shown in Figure 3.1 graphically shows the main four performance criteria and related overarching performance measures. As stated previously in section 2.4.2, the PRI formula is as follows (Garrett, 2012):

$$PRI = 0.45(Deficiency\ Points) + 0.45(100 - Sufficiency\ Rating) + 1.25(28 - (DK + SP + 2SB) + 10 \text{ if temporary shored} \quad (3.1)$$

where: *Deficiency Points* = *CP* + *WP* + *VP* + *LP*

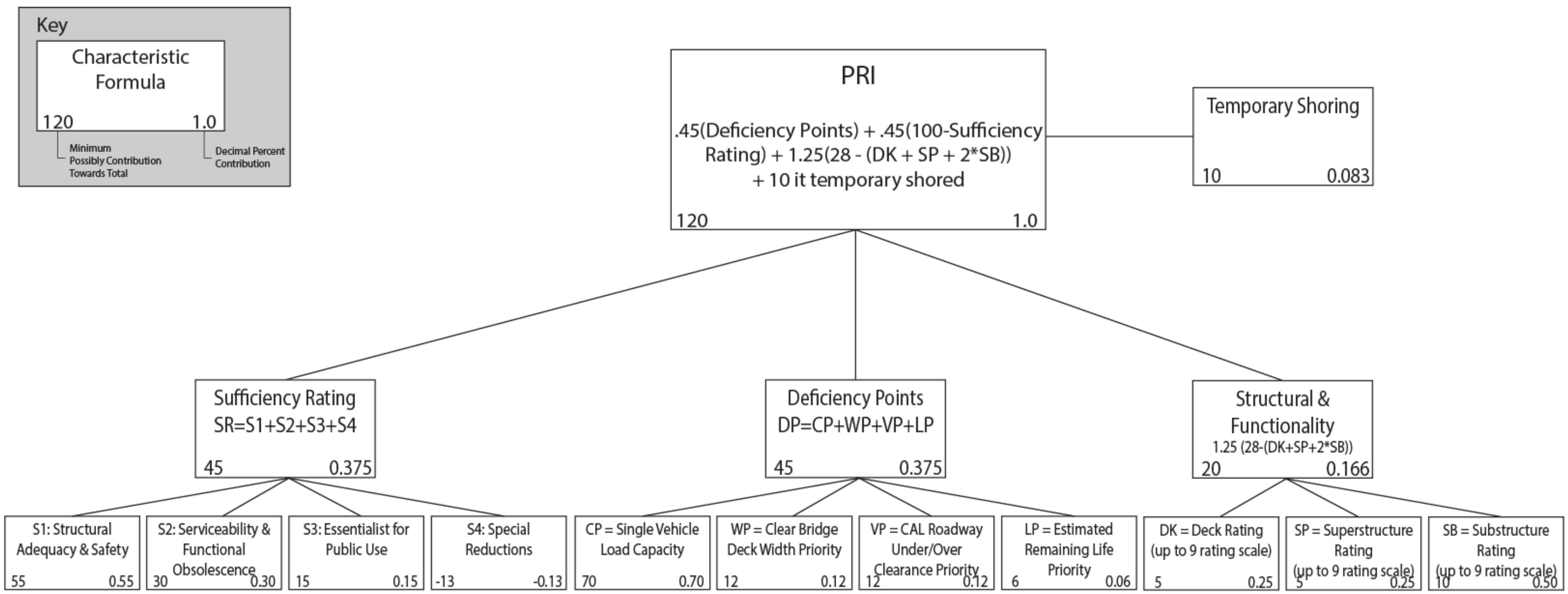
Sufficiency Rating = *S1* + *S2* + *S3* - *S4*

DK = Deck Rating

SP = Superstructure Rating

SB = Substructure Rating

In Section 3.1.3.1, an explanation of the contribution of deficiency points to the current PRI is presented, which is graphically shown in Figure 3.2. In Section 3.1.3.2, an explanation of the contribution of sufficiency rating to the current PRI is presented, which is graphically shown in Figure 3.3. Finally, in Section 3.1.3.3, an explanation of the contribution of structural and functionality components to the current PRI is presented, which is graphically shown in Figure 3.4.



PRI < 30 indicates not a good candidate for replacement
PRI > 30 & < 50 indicates a good candidate for replacement
PRI > 50 indicates a very good candidate for replacement

Figure 3.1: Priority replacement index diagram

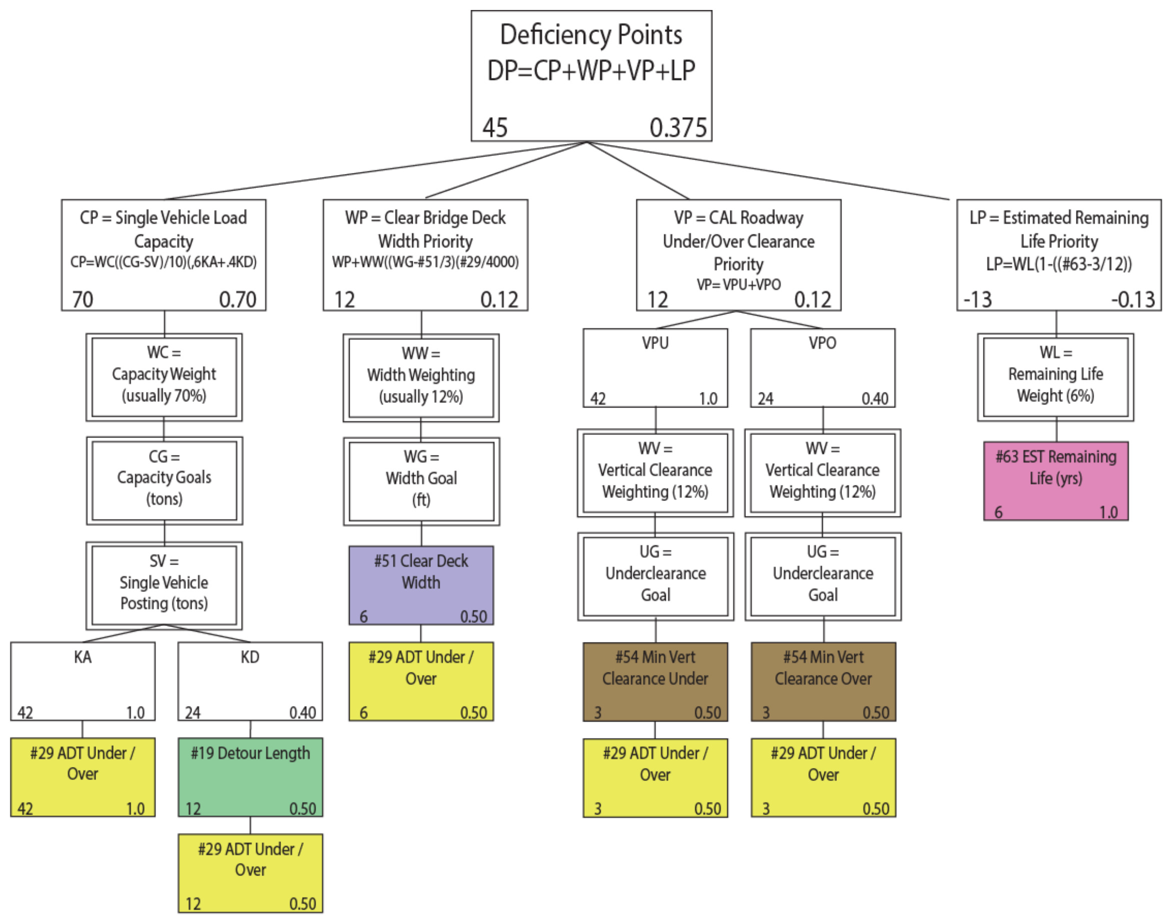


Figure 3.2: Deficiency points diagram

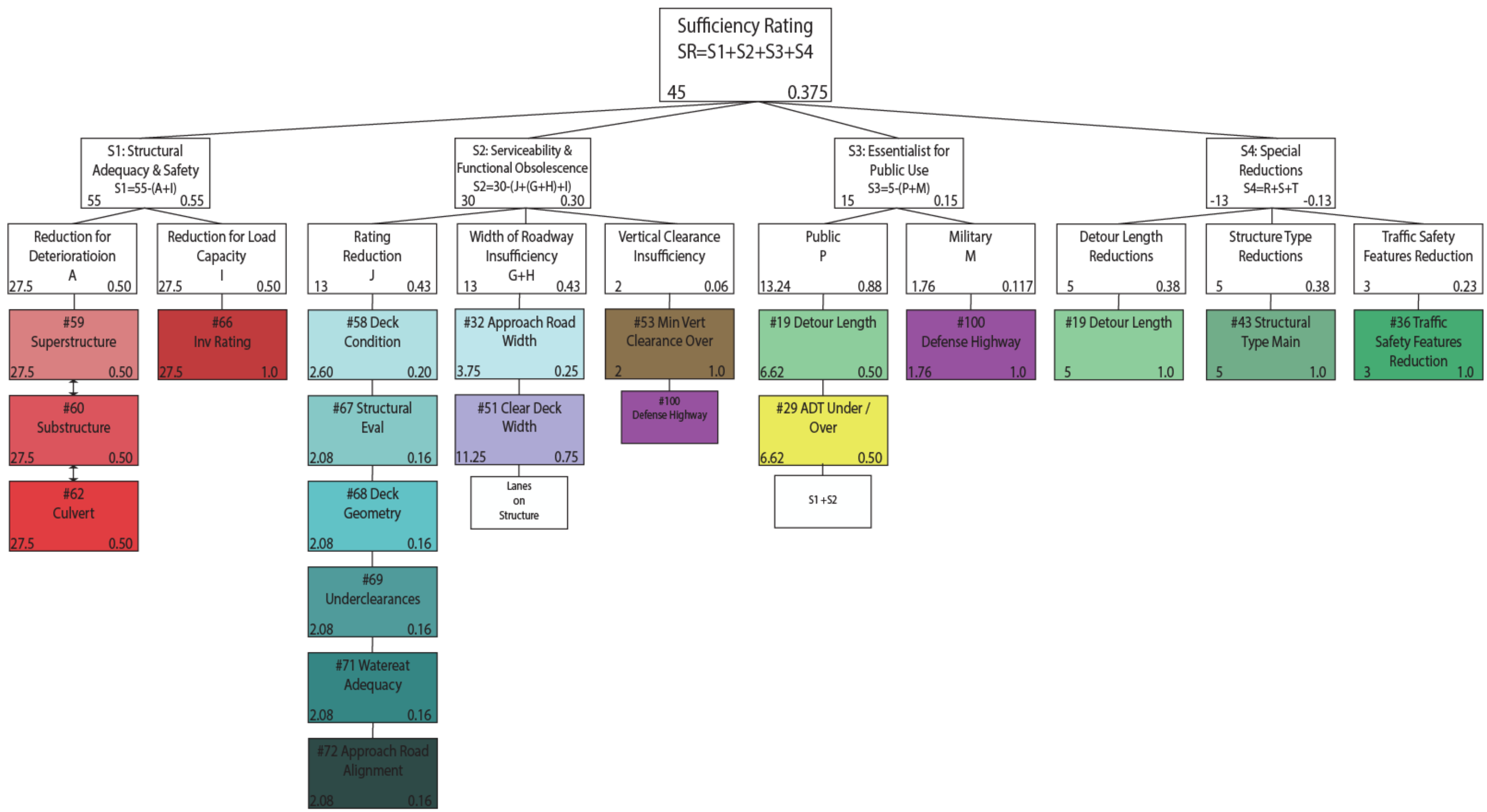


Figure 3.3: Sufficiency rating diagram

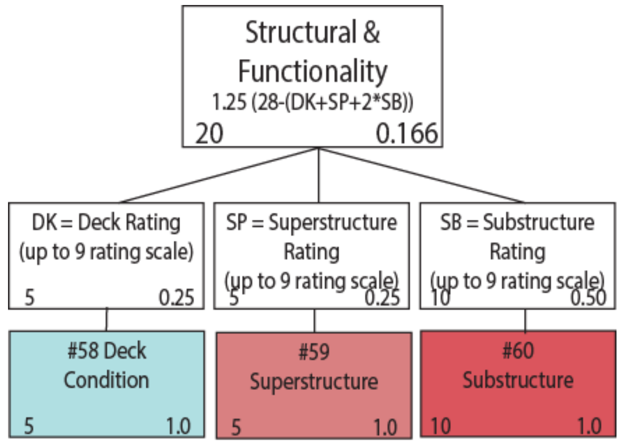


Figure 3.4: Structural and functionality diagram

Table 3.1: Priority index criteria point contribution

		Sufficiency Rating				Deficiency Points				Structural & Functionality			
Input I.D.	**Input Name**	**S1**	**S2**	**S3**	**S4**	**CP**	**WP**	**VP**	**LP**	**DK**	**SP**	**SB**	**TOTAL**
#19	Detour Length			6.62	5	12							23.62
#26	Functional Class												0
#28	Lanes on Structure												0
#29	ADT Under					54	6	6					66
#29	ADT Over			6.62		54	6	6					72.62
#32	Approach Safety Features (Road Width)		3.75										3.75
#36	Traffic Safety Features				3								3
#43	Structure Type Main				5								5
#51	Clear Deck Width (ft)		11.25				6						17.25
#53	Vertical Clearance Over (ft)		2					3					5
#54	Vertical Clearance Under (ft)							3					3
#58	Deck Condition		2.6							5			7.6
#59	Superstructure Rating	27.5									5		32.5
#60	Substructure Rating	27.5										10	37.5
#62	Culvert Rating	27.5											27.5
#63	Estimated Remaining Life (yrs)								6				6
#66	Inv Rating	27.5											27.5
#67	Structural Evaluation		2.08										2.08
#68	Deck Geometry		2.08										2.08
#69	Underclearances		2.08										2.08
#71	Waterway Adequacy		2.08										2.08
#72	Approach Roadway Alignment		2.08										2.08
#100	Defense Highway Designation			1.76									1.76

Total Points	**229.00**

Table 3.2: Priority index criteria percentage contribution

		Sufficiency Rating				Deficiency Points				Structural & Functionality			
Input I.D.	Input Name	S1	S2	S3	S4	CP	WP	VP	LP	DK	SP	SB	TOTAL
#19	Detour Length			0.0218	0.0214	0.0656							0.1088
#26	Functional Class												0
#28	Lanes on Structure												0
#29	ADT Under			0.0218		0.2231	0.0225	0.0226					0.29
#29	ADT Over					0.2231	0.0225	0.0226					0.2682
#32	Approach Safety Features (Road Width)		0.014										0.014
#36	Traffic Safety Features				0.0129								0.0129
#43	Structure Type Main				0.0214								0.0214
#51	Clear Deck Width (ft)		0.0422				0.0225						0.0647
#53	Vertical Clearance Over (ft)		0.0075					0.0113					0.0188
#54	Vertical Clearance Under (ft)							0.0113					0.0113
#58	Deck Condition		0.0097							0.0415			0.0512
#59	Superstructure Rating	0.103									0.0415		0.1445
#60	Substructure Rating	0.103										0.083	0.186
#62	Culvert Rating	0.103											0.103
#63	Estimated Remaining Life (yrs)								0.0225				0.0225
#66	Inv Rating	0.103											0.103
#67	Structural Evaluation		0.00778										0.00778
#68	Deck Geometry		0.00778										0.00778
#69	Underclearances		0.00778										0.00778
#71	Waterway Adequacy		0.00778										0.00778
#72	Approach Roadway Alignment		0.00778										0.00778
#100	Defense Highway Designation			0.00658									0.00658

Total Percentage	0.99158

3.1.3.1 Deficiency Points

Based upon the simplifying assumptions described previously, the Deficiency Points contribute 37.5% of the final PRI. They are calculated as (Chen and Johnson, 1984):

$$DP = CP + WP + VP + LP \tag{3.2}$$

where: *CP* = Single Vehicle Load Capacity Priority

WP = Clear Bridge Deck Width Priority

VP = Vertical Roadway Under / Over Clearance Priority

LP = Estimated Remaining Life Priority

The diagram for Deficiency Points includes all the contributing criteria, performance measures, and weights of each (Figure 3.2).

CP: Single Vehicle Load Capacity Priority

Single Vehicle Load Capacity Priority, CP, contributes up to 70% of the Deficiency Points and is calculated as (Johnson et al. 1984):

$$CP = WC \times ((CG - SV) / 10) \times (0.6\ KA + 0.4\ KD) \tag{3.3}$$

where: CP = capacity priority

WC = weight capacity

CG = capacity goal

SV = single vehicle posting

KA = average daily traffic

KD = detour length and average daily traffic

The CP formula is comprised of the bridge's weight capacity (WC), usually 70%, the capacity goal (CG) in tons, the single vehicle posting in tons, and the sum of KA and

KD. Note that this metric is bounded: any answer above 12 is capped at 12 and anything below 0 is entered as 0.

KA: Average Daily Traffic

KA, which accounts for the average daily traffic (NBI Item 29), is determined using the following formula (Johnson et al. 1984):

$$KA = (\#29)^{0.3} / 12 \tag{3.4}$$

KA can comprise up to 60% of the single vehicle load capacity goal or 42 points. This means that ADT Under / Over the bridge is up to 60% of the CP, up to 42% of the Deficiency Points, and 15.75% of the overall PRI when using the formula (1 × 0.6 × 0.7 × 0.375 = 0.1575), as shown in Table 3.1 and 3.2.

KD: Detour Length and Average Daily Traffic

KD accounts for the detour length (NBI Item 19) and average daily traffic (NBI Item 29), is found using the following formula (Chen and Johnson, 1984):

$$KD = (\#19 / 20)\,(\#29 / 4000) \tag{3.5}$$

Based on the assumptions utilized for this analysis, KD can in total comprise 40% of the single vehicle load capacity goal or 24 points. This results in both Detour Length and ADT accounting for 12 points or 20% of the CP. Therefore, both detour length and ADT are 14% of the Deficiency Points, and 5.25% of the overall PRI when using the formula (0.5 × 0.4 × 0.7 × 0.375 = 0.0525), as shown in Table 3.1 and 3.2.

In total, the CP comprises 70% of the Deficiency Points, and 26.25% of the overall PRI when using the formula (0.7 × 0.375 = 0.2625).Therefore, the CP is a significant portion of the PRI, which means that bridge replacement priority is significantly influenced by Average Daily Traffic and Detour Length.

WP: Clear Bridge Deck Width Priority

Clear Bridge Deck Width Priority, WP, comprises up to 12% of the Deficiency Points and is calculated as (Chen and Johnson, 1984):

$$WP = WW\,(WG - \#51 / 3)\,(\#29 / 4000) \tag{3.6}$$

where: *WP* = clear bridge deck width priority

WW = width weighting

WG = width goal

Where the given width weighting (*WW*) is usually 12% and accounts for both the clear deck width (#51) and ADT (#29).

Since both the clear deck width and the ADT are equal parts of the formula, they both comprise 6 points of the total 12 points for *WP*, or 50% each. Therefore, they contribute up to 6% of the *WP* and 2.25% of the total PRI when calculated as (0.5 × 0.12 × 0.375 = 0.0225), as shown in Table 3.1 and 3.2.

VP: CAL Roadway Under/Over Clearance Priority

CAL Roadway Under / Over Clearance Priority, VP, comprises up to 12% of the Deficiency Points and is calculated as (Chen and Johnson, 1984):

$$VP = VPU + VPO \tag{3.7}$$

where: *VP* = CAL roadway under / over clearance priority

VPU = vertical clearance under

VPO = vertical clearance over

VPU: Vertical Clearance Under

VPU, which accounts for the vertical clearance under (NBI Item 54) and average daily traffic (NBI Item 29), is found using the following formula (Chen and Johnson, 1984):

$$VPU = WV\ ((UG - \#54)\ /2)\ (\#29\ /\ 4000) \tag{3.8}$$

where: *WV* = vertical clearance weighting

UG = underclearance goal

The formula includes the vertical clearance weighting (*WV*), usually 12%, and the underclearance goal. Since both vertical clearance over and ADT are equal parts of the formula, each can contribute 3 points of the total 6 points for VPU or 50% of the VP. Therefore, they contribute up to 25% of the VP, 3% of the Deficiency Points, and 1.13% of the total PRI when calculated as (0.5 × 0.5 × 0.12 × 0.375 = 0.00125), as shown in Table 3.1 and 3.2.

VPO: Vertical Clearance Over

VPO which accounts for the vertical clearance over (NBI Item 3) and average daily traffic (NBI Item 29), is found using the following formula (Chen and Johnson, 1984):

$$VPO = WV\ ((UG - \#53)\ /\ 2)\ (\#29\ /\ 4000) \tag{3.9}$$

The formula includes the vertical clearance weighting (*WV*), usually 12%, and the overclearance goal. Since both vertical clearance over and ADT are equal parts of the formula, they can both be contribute 3 points of the total 6 points for VPO or 50% of the VP. Therefore, they comprise up to 25% of the VP, 3% of the Deficiency Points, and 1.13% of the total PRI when calculated as (0.5 × 0.5 × 0.12 × 0.375 = 0.00125), as shown in Table 3.1 and 3.2.

LP: Estimated Remaining Life Priority

Estimated Remaining Life Priority, LP, can comprise up to 6% of the Deficiency Points and is calculated as (Chen and Johnson, 1984):

$$LP = WL\ (1 - ((\#63 - 3) / 12)) \tag{3.10}$$

where: LP = estimated remaining life priority

WL = remaining life weighting

The formula includes remaining life weighting, WL, usually 6%, and is affected by the estimating remaining life (NBI Item 63), in years. Since estimating remaining life is the only input effecting the formula, it accounts for all 6 points. Therefore comprises 100% of the LP, up to 6% of the Deficiency Points, and 2.25% of the total PRI if calculated as (1 × 0.06 × 0.375 = 0.0225), as shown in Table 3.1 and 3.2.

3.1.3.2 Sufficiency Rating

Based on the assumptions outlined in Section 3.1.2 the sufficiency rating can contribute up to 37.5% of the final PRI. It is calculated as (Federal Highway Administration, 1995):

$$SR = S1 + S2 + S3 - S4 \tag{3.11}$$

where: SR = sufficiency rating

$S1$ = structural adequacy and safety

$S2$ = serviceability and functional obsolescence

$S3$ = essentiality for public use

$S4$ = special reductions

A similar schematic was created to estimate the total contribution of each characteristic to sufficiency rating, and this is shown in Figure 3.3.

S1: Structural Adequacy and Safety

S1: Structural Adequacy and Safety, which is 55% of the final SR, is calculated as (Federal Highway Administration, 1995):

$$S1 = 55 - (A + I) \tag{3.12}$$

where: A = reduction for deterioration

I = reduction for load capacity

Reduction for Deterioration: A

Reduction for deterioration (A) is produced by taking the lowest score of either the superstructure rating (NBI Item 59), the substructure rating (NBI Item 60), or the culvert (NBI Item 62). If the lowest number is less than or equal to 2, then A = 55. If the lowest score is equal to 3, then A = 40. If the lowest number is equal to 5, then A = 10. If the lowest number is less than 5, then A = 0.

Reduction for Load Capacity: I

The second part reduction for load capacity (I) is calculated as (Federal Highway Administration, 1995):

$$I = 0.2278\,(36 - IR)^{1.5}. \tag{3.13}$$

where: I = Load Capacity

IR = Inventory Rating

To find IR, the second and third digit of the Inventory Rating (NBI Item 66) are utilized. Note that if the IR is less than 36 then I= 0. An example of this equation, if I and A are assumed to be zero, is S = 55 – (0 + 0) = 55. Based on this equation, if I and A

equal are assumed to be equal, they comprise 55% of the final percentage S1 contributes to the Sufficiency Rating. Therefore, both *I* and *A* are 27.5% of the SR. Since SR is 37.5% of the PRI which would make *I* and *A* each comprise 10.3% of the final rating when equal, as shown in Table 3.1 and 3.2.

S2: Serviceability and Functional Obsolescence

S2: Serviceability and Functional Obsolescence, which is 30% of the final SR, is calculated as (Federal Highway Administration, 1995):

$$S2 = 30 - (J + (G + H) + I) \tag{3.14}$$

where: J = rating reduction

$G + H$ = width of roadway insufficiency

I = vertical clearance insufficiency

Rating Reduction: J

Rating reduction (J), is 13% of S2 at maximum value and calculated as (Federal Highway Administration, 1995):

$$J = A + B + C + D + E + F \tag{3.15}$$

Where: J = rating reduction

A = deck condition (NBI Item 58)

B = structural evaluation (NBI Item 67)

C = deck geometry (NBI Item 68)

D = underclearances (NBI Item 69)

E = water adequacy (NBI Item 71)

F = approach roadway alignment (NBI Item 72)

Table 3.3: Rating reduction point values (Federal Highway Administration, 1995)

Element	**Scores**			
A	5 if less than or equal to 3	3 if equal to 4	1 if equal to 5	0 if greater than 5
B	4 if less than or equal to 3	2 if equal to 4	1 if equal to 5	0 if greater than 5
C	4 if less than or equal to 3	2 if equal to 4	1 if equal to 5	0 if greater than 5
D	4 if less than or equal to 3	2 if equal to 4	1 if equal to 5	0 if greater than 5
E	4 if less than or equal to 3	2 if equal to 4	1 if equal to 5	0 if greater than 5
F	4 if less than or equal to 3	2 if equal to 4	1 if equal to 5	0 if greater than 5

If each score equals its highest possible value, then the total is 25. However, the total score for J is restricted to 13. Therefore, if the total is more than 13, then the total score for J becomes 13. To determine the total maximum points and percentage weight each component can contribute, the values must be normalized from the total of 25 to the restricted total value 13, as shown in Table 3.1 and 3.2.

Each performance measure also contributes a percentage to J and the overall PRI. To calculate A, take 5 / 25= 0.2, then multiply 0.2 × 13= 2.6. The total number of points *A* can contribute to the SR is 2.6. To find the percentage contribution of A to SR divide 2.6 by 13, resulting in A having a contribution of 20% of J. Since J is 13 points or 43%, 13 / 30 = 0.433, of the 30% of S2, and the SR is 37.5% of the total PRI, to find the overall percentage, multiply (0.2) × (0.433) × (0.3) × (0.375) = 0.0097 or 0.97%. Therefore A, which is Deck Condition, is 0.97% of the total PRI, shown in Table 3.1 and 3.2.

The performance measure Structural Evaluation, or B, is calculated by taking 4 / 25 = 0.16, then multiplying 0.16 × 13 = 2.08. Therefore, the total number of points B can contribute to the SR is 2.08. The percentage contribution of *B* to SR is calculated by dividing 2.08 by 13, resulting in *B* having a contribution of 16% of J. Again, J is 13 points or 43%, 13 / 30 = 0.433, of the 30% of S2, and the SR is 37.5% of the total PRI. To find the overall percentage, one would multiply (0.16) × (0.433) × (0.3) × (0.375) = 0.00778 or 0.78%. This means that B, or Structural Evaluation, is 0.78% of the total PRI. Since *C* through *F* have the same maximum point value as *B*, they are all equal to the same percentage of *B* at 0.78% of the PRI, as shown in Table 3.1 and 3.2.

Width of Roadway Insufficiency: G+H

Width of Roadway Insufficiency (designated as G + H) is worth 15% of the SR or 50% of S2. The equation for G + H is simply (Federal Highway Administration, 1995):

$$G + H \tag{3.16}$$

where: *G* =

- 0 if Culvert
- 5 if (Bridge Road Width + 2' < Appropriate Road Width)
- 0 if anything else

H = (based on the *X* and *Y* values)

- 15 if the bridge road width is less than 14'
- 15 if the bridge road width is between 15' and 16'
- 0 if anything else

To determine the total maximum points that these characteristics can contribute to the Sufficiency Rating, each component must be normalized since *G* can have a maximum of 5 points and *H* can have a maximum of 15 points. Together, the sum of *G*+*H* can be 20 points, but *G* + *H* is capped at 15 points. Once normalized, *G* can have a maximum of 3.75 points or 25% of Width of Roadway Insufficiency and *H* can have 11.25 points or 75%. Therefore, *G* is 3.75% of the SR and 1.4% of the overall PRI when calculated using ($0.25 \times 0.5 \times 0.3 \times 0.375 = 0.014$). Which makes *H* 11.25% of the SR and 4.2% of the total PRI when calculated using ($0.75 \times 0.5 \times 0.3 \times 0.375 = 0.0422$), as shown in Table 3.1 and 3.2.

Vertical Clearance Insufficiency: I

Vertical Clearance Insufficiency is worth up to 2% of the SR or 6.67% of S2. This item is describes the "actual minimum vertical clearances over the bridge roadway, including the shoulders, to any superstructure restriction" (Federal Highway Administration, 1995). According to the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, the number is determined by:

- If no restriction then 9999
- 5.25 meters then 0525
- 23.00 meters then 2300
- 38.50 meters then 9999

The point value for the PRI is as follows:

- if less than 1600 and Defense Highway Designation is greater than 0
- if less than 1400 and Defense Highway Designation is equal to 0
- 0 if anything else

Since I is the only component of the Vertical Clearance Insufficiency, it accounts for 100% of the 6.67% of S2. Since I is 2% of the SR, it is therefore 0.75% of the total PRI when calculated using ($1.0 \times 0.067 \times 0.3 \times 0.375 = 0.0075$), as shown in Table 3.1 and 3.2.

S3: Essentiality for Public Use

S3: Essentiality for Public Use comprises 15% of the SR and is calculated as (Federal Highway Administration, 1995):

$$S3 = 15 - (P + M) \qquad (3.17)$$

where: *P* = public

M = military

Public: P

Public is calculated as the following (Federal Highway Administration, 1995):

$$P = (ADT \times Detour \times 15) / (200{,}000 \times K)$$

$$K = (S1 + S2) / 85 \qquad (3.18)$$

Therefore, the maximum value *P* can have is 15 if P1 is anything greater than 15. If P1 is below 15, then it equals whatever the equation produces based on the inputs of the components.

Military: M

Military is calculated simply by the following point system:

- if greater than 0
- 0 if equal to 0

Since *P* and *M* have a maximum value of 17, they must also be normalized to determine their overall value. This would result in *P* and *M* having the maximum value of 13.24, or 88% of S3. Which would be equally split between ADT and Detour at 6.62 points each and 44%. H has a maximum value of 1.76 or 11.7% of S3. Therefore, *P* would be 13.2% of the SR and 4.95% of the total PRI, making both ADT and Detour 2.18% if calculated as (0.44 × 0.88 × 0.15 × 0.375 = 0.02178). *H* would be 1.17% of the

SR and 0.66% of the total PRI if calculated as (1.0 × 0.117 × 0.15 × 0.375 = 0.00658), as shown in Table 3.1 and 3.2.

S4: Special Reductions

S4: Special Reductions comprise up to 13% of the SR, and is calculated as (Federal Highway Administration, 1995):

$$S4 = R + S + T \tag{3.19}$$

where: R = detour length reductions

S = structure type reductions

T = traffic safety features reduction

This category is only calculated when S1 + S2 + S3 are greater than or equal to 50.

Detour Length Reduction: R

Detour Length Reduction, R, is 5% of SR and defined by the equation (Federal Highway Administration, 1995):

$$R = [Detour \times 4 \times 5.205 \times 10^{-8}] \tag{3.20}$$

R only becomes a factor if the detour length is greater than 30. R has a maximum of 5 when the detour is at maximum of 99 miles. Therefore, since R has a maximum of 5 points, it is 38% of S4, 5% of SR and 2.14% of the total PRI if calculated (0.38 × 0.15 × 0.375 = 0.0214), as shown in Table 3.1 and 3.2.

Structure Type Reduction: S

Structure Type Reduction, S, is 5% of SR and defined by:

- 5 if the 2nd and 3rd digits of NBI Item 43 (Structure Type Main) are 10 or 12-17
- 0 if the 2nd and 3rd digits of NBI Item 43 (Structure Type Main) are anything else

Since *S* has a maximum of 5 points, it is 38% of S4, 5% of SR and 2.14% of the total PRI if calculated (0.38 × 0.15 × 0.375 = 0.0214), as shown in Table 3.1 and 3.2.

Traffic Safety Features Reduction: T

Traffic Safety Features Reduction, *T*, is 3% of SR and defined by:

- 3 if NBI Item 36 (Traffic Safety Features) has 4 zeros
- 2 if NBI Item 36 (Traffic Safety Features) has 3 zeros
- 1 if NBI Item 36 (Traffic Safety Features) has 2 zeros
- 0 if NBI Item 36 (Traffic Safety Features) has anything else

Since *T* has a maximum of 3 points, it is 23% of S4, 3% of SR and 1.23% of the total PRI if calculated (0.23 × 0.15 × 0.375 = 0.0129) , as shown in Table 3.1 and 3.2.

3.1.3.3 Structural and Functionality

Structural and Functionality (S&F) make up 20 points and 16.6% of the PRI, and calculated as the following:

$$1.25\ (28 - (DK + SP + (2 \times SB))) \quad (3.21)$$

where: *DK* = deck rating

SP = superstructure rating

SB = substructure rating

Each bridge is inspected by a state bridge inspector, who provides a rating for the deck, superstructure, and substructure during each inspection. The rating is then entered into the NCDOT BMS. From there, the value can be utilized in computing the individual bridge’s PRI. It is important to note that in this section the higher the rating, the better the condition of the bridge. Therefore, if the deck, superstructure, and substructure all had the highest rating, they would reduce this part of the PRI, causing the overall PRI to be lower. To evaluate the contribution of bridge characteristics to this metric, the same type of schematic was also created for the Structural and Functionality component as was constructed for the other three contributors to the PRI. This diagram is shown in Figure 3.4.

DK: Deck Rating

Deck Rating (*DK*), which makes up 25% of the S&F score can have a total of 5 points. Decks can be rated on a scale of 9 to 0 (Federal Highway Administration, 1995). Bridges with ratings over 7 are not considered for bridge prioritization, though according to the current PRI information, a deck is only considered structurally deficient if it has a rating of 4 or less. Since this portion of the rating can be up to 5 points of 20, 9 must be normalized, which then is equal to 5. So, the deck rating is up to 25% of the S&F and 4.15% of the total PRI if calculated as ($0.25 \times 0.166 = 0.0415$), as shown in Table 3.1 and 3.2.

SP: Superstructure Rating

Superstructure Rating (*SP*), which comprises up 25% of the S&F, can have a total of 5 points. The superstructure can be rated on a scale of 9 to 0 (Federal Highway Administration, 1995). Bridges with an overall score of 7 are not considered for bridge prioritization, though according to the current PRI information, the superstructure is only considered structurally deficient if it has a rating of 4 or less (Federal Highway Administration, 1995). Since this portion of the rating can be up to 5 points of 20, 9 must be normalized, which then is equal to 5. So, the superstructure is up to 25% of the S&F

and 4.15% of the total PRI if calculated as (0.25 × 0.166 = 0.0415) , as shown in Table 3.1 and 3.2.

SB: Substructure Rating

Substructure Rating (*SB*), which comprises up 50% of the S&F, can have a total of 10 points. The substructure can be rated on a scale of 9 to 0 (Federal Highway Administration, 1995). Bridges with an overall score of 7 are not considered for bridge prioritization, though according to the current PRI information, the substructure is only considered structurally deficient if it has a rating of 4 or less. Since the rating can only be up to 10, normalize 9, which then is equal to 5, but since it is multiplied by two, it is 10. So, the deck rating is up to 50% of the S&F and 8.3% of the total PRI if calculated as (0.50 × 0.166 = 0.083), as shown in Table 3.1 and 3.2.

3.2 Summary of Impact of Bridge Criteria and Measures on PRI

As discussed previously, the total contributions of each bridge performance measure to the PRI were analyzed. These tables (Table 3.1 and 3.2) were presented in section 3.1.1 with further analysis provided here in the chapter summary. In Table 3.1 and Table 3.2, the maximum possible point contribution and decimal percent is listed for each characteristic. Numbers formatted in red indicate that a particular characteristic could be selected in lieu of other characteristics based upon the given selection for each. For example, the Deficiency Point formula requires the choice between ADT Under and ADT Over. When ADT is greater than 4000, ADT Over is selected, but if ADT is under 4000, ADT Under is selected. Therefore, in Tables 1 and 2, the red text color is used to indicate that only one of the characteristics is actually included in computing the total designated points or percent.

From these Tables, it is apparent that the characteristics that most significantly influence the PRI are:

- #29 ADT Over at 72.62 points and 29% of PRI (at maximum)
- #60 Substructure Rating at 37.5 points and 18.6% of PRI (at maximum)
- #59 Superstructure Rating at 32.5 points and 14.5% of PRI (at maximum)
- #19 Detour Length at 23.62 points and 10.8% of PRI (at maximum)

These performance measures are largely related to traffic, bridge condition, and indirectly to safety. Through this analysis, it can be seen that measures included in the STI Law to determine the prioritization of transportation project are not highly reflected in the PRI. For example, in P4.0, Statewide Strategic Mobility Projects consider Multimodal, Freight, and Military performance criteria with a total relative weighting of 20%. Although these factors are considered in the PRI in the Sufficiency Rating, it only accounts for 0.66% of the total PRI. This is significantly less and underrepresented when compared to the preferences of the STI legislation. Also apparent from inspection of Table 3.2 and Table 3.3 is the fact that some characteristics influence the PRI through multiple performance criteria. For example, #51 Clear Deck Width influences the PRI through both the sufficiency rating and deficiency points.

3.3 Compliance of Current Bridge Prioritization to Legislative Requirements

Performance criteria outlined in MAP-21 and the STI differ, since the two laws were written in relation to non-bridge transportation projects. MAP-21 metrics were developed to calculate at a network-level with a focus on statewide performance tracking, while the STI was developed by the NCDOT to address project-level criteria and measures. Although bridges are specifically excluded from STI prioritization requirements, it is important that the proposed measures reflect the spirit of this legislation as much as possible in order to promote clarity and consistency in highway infrastructure project prioritization. By using consistent criteria, bridge replacement projects will become more competitive when competing for funding with other transportation projects that are subjective to the STI legislation.

3.4 Recommended Modifications

The analysis of the PRI presented in this chapter has demonstrated that there are currently many factors influencing the prioritization. Some factors are essentially double-counted (influencing the PRI through multiple performance criteria such as deficiency points and sufficiency rating), while other characteristics that could be linked to current federal and state goals do not appear in the current PRI. Other characteristics were shown to influence the current PRI, but are not weighted in a manner that is consistent with state and federal guidance. For example, Multimodal, Freight, and Military importance should be considered in Statewide Strategic Mobility Projects (at a contribution of 20%) (NCDOT, 2015). However, the only measure linked to this criteria is STRAHNET designation, which comprises only 0.66% of the rating, indicating it is highly underrepresented in the current PRI. Ultimately, a new set of performance criteria should be recommended to NCDOT for consideration that more adequately reflects federal and state goals, with weighting more in line with agency preferences and risk tolerance.

CHAPTER 4: ANALYSIS OF MAINTENANCE BURDEN AND MAINTENANCE NEEDS DATA

Bridge maintenance costs transportation departments millions of dollars each year. According to the U.S. Government Accountability Office (GAO), 14 out of 24 states interviewed express the lack of adequate funding for bridges (GAO, 2016). As an example, Louisiana DOTD recently informed the GAO that they have a backlog of $12 billion for bridge and road projects, which due to the lack of funding is causing bridges to exceed the 10 percent threshold for structurally deficient bridge deck areas (GAO, 2016). Not only does the state need more funding for replacement, but they are spending significant amounts of money on maintenance to keep a bridge functioning until they can allocate funds to replace it. NCDOT is also currently in a position where many bridges in the state's inventory have substantial maintenance needs, and the maintenance activities (burden) being performed are consuming a significant amount of already limited resources. Currently, a significant backlog of maintenance needs identified annually by bridge inspectors exists, and NCDOT personnel have expressed desires to the research team for the project supporting this thesis work that these maintenance needs, along with the burden of maintenance activities performed, be included in development of new prioritization indices for bridge replacement, repair, and rehabilitation.

In order to identify the best means of incorporating maintenance needs and maintenance burden into the prioritization criteria and measures and to justify their use, an analysis of maintenance burden and maintenance needs data was performed. The objectives of this analysis were to identify the key bridge maintenance actions (for both needs and burden) linked to bridges either scheduled for replacement or considered for replacement, determine the costs associated with these activities, and suggest performance criteria and measures that could be utilized in a proposed new bridge project prioritization index. To accomplish this, maintenance burden and maintenance needs data provided by NCDOT was analyzed for two sets of bridges:

- Bridges currently scheduled for replacement (identified in the BMIP plans in the BMS), a total of 682 bridges, and
- Bridges currently flagged as "consider for replacement" in the BMS network master, but not currently listed in the BMIP plans in the BMS, a total of 770 bridges. These bridges are subsequently referred to as "flagged for replacement but not scheduled."

Each data set was analyzed separately, and the following sections present the methodology used in the analyses, along with key findings. At the end of this chapter, recommendations for incorporating performance criteria and measures for both maintenance needs and maintenance burden are presented.

4.1 Maintenance Burden

NCDOT personnel report that recurring maintenance activities associated with specific bridges drive division personnel to identify these structures for prioritization for replacement. In addition to the costs associated with these maintenance actions continually being performed, other issues such as worker safety and additional administrative workload exist, increasing the impact of these activities on NCDOT's limited resources.

4.1.1 Sources of Maintenance Burden Data

Maintenance history (burden) data was obtained from the NCDOT Asset Management System (AMS), as provided by NCDOT personnel (Mr. Matthew Whitley, Maintenance Management and Analysis Engineer). This dataset included all recorded maintenance actions performed from the early 2000's to 2016. This included records of 67,114 maintenance cases performed on a total of 13,223 bridges. Each maintenance activity record was linked to a structure number, and included information such as:

- Structure number
- Activity name
- Start date
- Amount (quantity)
- Labor cost, equipment cost, material cost, and total cost

It is important to note that according to Mr. Whitley, it is estimated that only 30 to 60% of maintenance actions performed on a given structure may have actually been recorded and included in this dataset. Despite this limitation, this dataset can be assumed to provide a reasonable record of activities that could be utilized for analysis to support identification of performance criteria and measures for bridge project prioritization. Additionally, it is recognized by NCDOT personnel that linking these maintenance activities to a prioritization index may encourage division personnel to improve the rate of recording such maintenance activities in the future.

4.1.2 Preparation of Dataset for Analysis

Prior to performing the analysis, several steps to prepare the dataset were performed. First, maintenance burden records for bridges neither scheduled for replacement nor flagged for replacement were removed from the dataset. The limited number of records for maintenance activities occurring prior to 2007 were removed. Additionally, maintenance records for types of activities not relevant to replacement, such as records associated with activities such as vegetation removal and routine inspection, were removed. The dataset resulting after this preparation included a list of 2,487 maintenance action cases associated with 896 bridges.

4.1.3 Analytical Approach

To justify use of maintenance history data in bridge project prioritization, and to identify performance criteria and measures that could be recommended for use in a future index, the costs of specific types of maintenance activities were analyzed, as well as the costs of reoccurring maintenance activities. This approach was utilized in hopes of incorporating the impact of both high-cost but low-occurrence maintenance actions as well as low-cost but frequently reoccurring maintenance actions into the recommended prioritization metrics.

As part of this analysis both cost and occurrence of aspects of maintenance activities, both reoccurring and non-reoccurring, were quantified and reviewed. The analysis process started with determining which maintenance actions had reoccurring cases, then listing the total number of bridges receiving that maintenance action and the number of cases of that action performed. For each reoccurring and non-reoccurring maintenance type data was manipulated to compute various measures of cost and occurrence. In the following sections, a summary of key findings from this analysis are presented, with tables and graphics to illustrate the trends observed.

4.1.4 Analysis Methodology and Results

As stated previously, one of the key goals of the project was evaluate the impact of reoccurring maintenance actions, which for this dataset means the same maintenance action has been performed on a single bridge at least twice over the past 10 years. In Table 4.1, a summary of reoccurring maintenance actions that occurred for bridges both scheduled for replacement, as well as flagged but not scheduled for replacement are listed. Although Table 4.1 includes a list of all recurring maintenance actions, a copy of the full table is shown in Appendix A, Table A.1., which provides additional information such as average number of reoccurring cases per bridge, total number of cases, total quantities, and total cost. Additional details describing computations supporting this table, and presenting a description of the data summarized in Table A.1, is presented after the Table.

Table 4.1: Summary of analysis of reoccurring and non-reoccurring maintenance actions for previously prioritized bridges

Reoccurring Maintenance Factors for Bridges:	Number of Bridges with 2 or more cases of reoccurring (# of bridges)	Total Number of Reoccurring Cases	Number of Non-reoccurring Cases	Total Cost of Reoccurring Maintenance	Average Cost of Reoccuring Maintenance	Non-reoccurring Maintenance Cost	Average Cost of Non-reoccruing Manitenance	Percent of reoccurring bridges to to Total # of bridges	Percent of Bridges with Maintenance Action Performed
Asphalt Pavement Repair and Patching	2	6	24	$ 22,927.99	$ 3,821.33	$ 49,261.63	$ 2,463.08	0.22%	2.46%
Maintain Timber Superstructure Components	10	23	60	$ 376,241.98	$ 16,358.35	$ 526,543.41	$ 11,203.05	1.12%	6.36%
Maintain Concrete Superstructure Components	13	27	65	$ 411,009.65	$ 15,222.58	$ 480,967.87	$ 9,430.74	1.45%	7.14%
Maintain/Repair Bridge Exp. Joint	13	27	68	$ 131,946.56	$ 4,886.91	$ 151,327.52	$ 2,802.36	1.45%	7.48%
Maintain Steel Superstructure Components	30	68	163	$ 2,125,939.00	$ 31,263.81	$ 1,613,607.51	$ 12,908.86	3.35%	17.30%
Maintain Timber Deck Components	22	64	115	$ 583,641.60	$ 9,119.40	$ 1,293,953.19	$ 17,725.39	2.46%	10.60%
Maintain Concrete Deck	16	56	92	$ 782,618.40	$ 13,975.33	$ 459,385.45	$ 8,834.34	1.79%	7.59%
Maintain/Repair/Replace Steel Plank Bridge Floor	4	13	20	$ 96,484.94	$ 7,421.92	$ 110,656.13	$ 10,059.65	0.45%	1.67%
Maintain Movable Bridges	1	12	15	$ 551,106.59	$ 45,925.55	$ 9,846.85	$ 2,461.71	0.11%	0.56%
Operations of Movable Bridges	1	6	5	$ 1,412,547.93	$ 235,424.66	$ -	$ -	0.11%	0.11%
Repair/Replace Timber Substructure Components	42	95	250	$ 1,531,766.83	$ 16,123.86	$ 2,290,851.19	$ 11,628.69	4.69%	26.67%
Repair/Maintain Timber Wings and Blkhds.	20	42	130	$ 599,031.03	$ 14,262.64	$ 810,577.17	$ 7,505.34	2.23%	14.29%
Maintain Concrete Substructure Components	8	16	68	$ 240,029.41	$ 15,001.84	$ 1,082,779.02	$ 18,046.32	0.89%	7.59%
Maintain Slope Protection	2	4	61	$ 198,591.32	$ 49,647.83	$ 257,175.08	$ 4,358.90	0.22%	6.81%
Maintain / Repair Steel Substructure Components	4	10	26	$ 161,144.93	$ 16,114.49	$ 775,371.51	$ 38,768.58	0.45%	2.68%
Maintenance and Repair of Fender System	1	3	3	$ 139,327.47	$ 46,442.49	$ 337.50	$ 337.50	0.11%	0.22%
Maintain Concrete Bridge Floor	1	2	15	$ 10,600.96	$ 5,300.48	$ 75,280.62	$ 5,377.19	0.11%	1.67%
Repair Steel Plank Bridge Floor	1	2	3	$ 2,756.27	$ 1,378.14	$ 8,014.13	$ 4,007.07	0.11%	0.33%
Maintain Deck Expansion Joints	2	4	18	$ 13,236.73	$ 3,309.18	$ 27,394.09	$ 1,712.13	0.22%	2.01%
Maintain Timber Piles and Posts	1	2	13	$ 38,979.71	$ 19,489.86	$ 87,655.11	$ 7,304.59	0.11%	1.45%
Bridge Installation and Repair	2	4	8	$ -	$ 37,859.93	$ 382,210.45	$ 63,701.74	0.22%	0.89%
Maintain Steel Plate Bridge Joint	1	2	2	$ 5,342.38	$ 2,671.19	$ 7,725.68	$ 7,725.68	0.11%	0.22%

The first step in the analysis included defining the reoccurring maintenance actions, the total number of bridges that had the reoccurring maintenance and the total number of reoccurring cases. For example, as shown in the first line of Table 4.1, there are two bridges with reoccurring maintenance of asphalt pavement repair and patching with a total of 6 reoccurring cases. Next, the average number of cases for bridges was determined by dividing the number of cases by the number of bridges.

For each maintenance type, the total number of cases with that type of maintenance action was determined for both reoccurring and non-reoccurring maintenance actions. This was used to find the percentage of reoccurring cases. For example, as shown in the first line of Table 4.1, there are 26 total cases for asphalt pavement repair and patching. By dividing the reoccurring cases (6) by the total number of cases (26), the result is the percentage of cases that are reoccurring (23%). This same step was repeated, but was sorted by the total number of bridges that received the maintenance type instead of cases. Since there were records for 2 bridges with reoccurring cases of asphalt pavement repair and patching and 22 total bridges, the number of bridges reoccurring cases was divided by the total number of bridges to get the percentage of bridge with reoccurring maintenance (9%).

Similarly, the percentage of bridges with reoccurring maintenance action(s) was also compared to the total number of bridges in the dataset was computed. For instance, asphalt pavement repair and patching was performed as reoccurring maintenance on 2 bridges, which is divided by 896 total bridges, resulting in 0.22% of bridges with this reoccurring maintenance activity.

Similarly, the percentage of bridges with the maintenance action performed but not reoccurring was calculated by taking the total number of bridges with that maintenance action and dividing it by the total number of bridges in the data set. For the example maintenance action of asphalt pavement repair and patching, which was performed on 22 total bridges, was divided by the total of 896 total bridges to indicate that 2% of all bridges have had maintenance actions for asphalt pavement repair and patching (as shown in the first line of Table 4.1).

Additional analysis was performed to evaluate the cost associated with each type of maintenance action. First, the total cost of each type of maintenance action was determined, including both reoccurring and non-reoccurring cases. Then, the total cost of only reoccurring maintenance actions of each type was computed. To determine the average cost of reoccurring maintenance, the total cost of reoccurring maintenance was divided by the number of reoccurring cases. For example, as shown in the first line of Table 4.1, asphalt pavement repair and patching has a total reoccurring maintenance cost of $22,927.99 and 6 reoccurring cases. Dividing the total cost of reoccurring cases by the number of reoccurring cases, results in an average cost of $3,821.33 per case. Similarly, the average cost of non-reoccurring maintenance cases was determined. First the total cost of non-reoccurring cases was computed. This figure was divided by the total number of non-reoccurring cases. For the example maintenance action of asphalt pavement repair and patching, a non-reoccurring maintenance cost of $49,261.63 was computed. When divided by the total number of non-reoccurring cases (24), an average cost of $2,463.08 per non-reoccurring case is determined.

In addition to the summary table (Table A.1) presenting the results of this analysis, two graphs were developed to illustrate the percentage of maintenance performed each year on bridges scheduled or flagged for replacement, and the total cost of that maintenance. In Figure 4.1, the percentage of maintenance work performed each year for both scheduled and non-scheduled bridges is shown. To produce this graph, data was normalized by dividing the total number of cases per year by the total number of bridges to determine the percentage of maintenance work performed each year for both scheduled and flagged but not scheduled bridges. In Figure 4.2, the average total cost of maintenance performed per bridge each year for both scheduled and flagged but not-scheduled bridges is shown. In this graph, data has also been normalized, with each yearly total divided by the total number of bridges to determine the average total cost spent on each bridge annually. It is noted that 2016 data was likely not complete at the time of this work, resulting in the artificially low values for this year in both Figure 4.1 and 4.2.

From Figure 4.1, it is shown that from 2007 to 2013, a relatively equal amount of maintenance performed each year (11%). More recently, this percentage has dropped, but for reasons not known to the author. However, in Figure 4.2, which displays the average total cost per year spent on maintenance actions for bridges scheduled for replacement and bridges flagged for replacement but not scheduled, from year to year some significant variation in average annual cost of maintenance does occur. The average annual maintenance cost per bridge ranges from approximately $2,200 to $3,500, with 2016 data artificially low due to the dataset being incomplete for this year at the time of this publication.

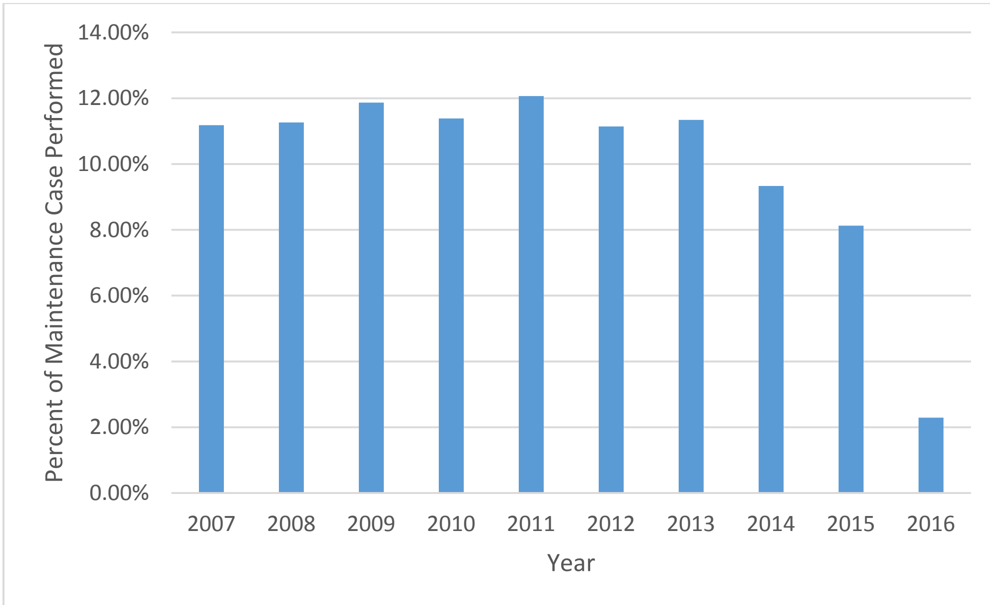


Figure 4.1: Percent of maintenance work performed yearly for both scheduled and flagged but not scheduled bridges

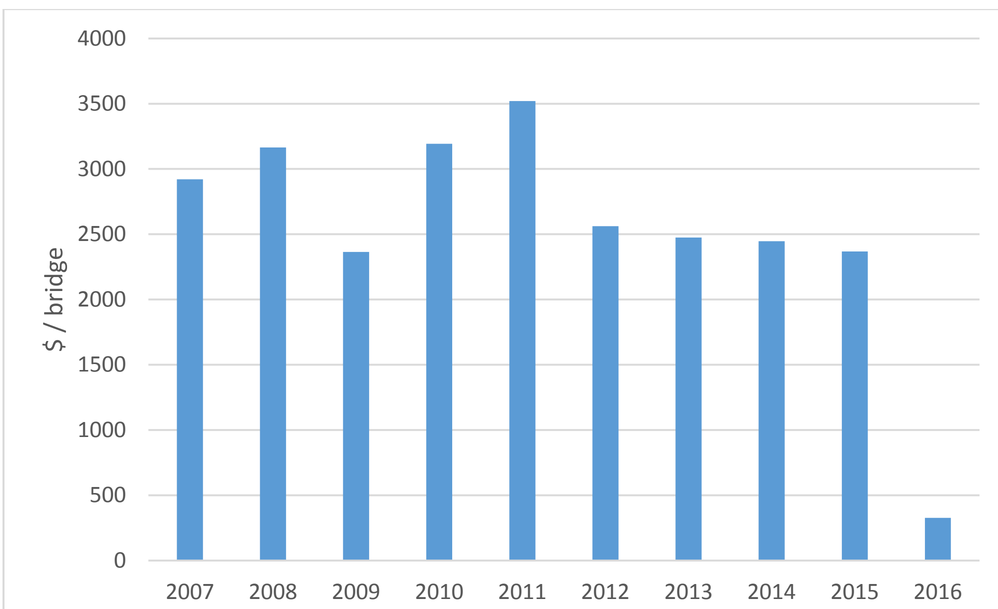


Figure 4.2: Average total cost of yearly maintenance per bridge for scheduled and flagged but not scheduled bridges

From this analysis, it can be seen that of the maintenance performed over the past ten years, a total of 20 maintenance types appear as reoccurring maintenance types. Of these, three actions have the most reoccurring cases:

- maintain steel superstructure components
- maintain timber deck components
- maintain timber substructure components

Other types of maintenance actions, such as maintain timber superstructure components, maintain concrete superstructure components, maintain bridge expansion joints, and maintain concrete deck, also have a higher amounts of reoccurring cases.

The process described above was repeated two more times, after dividing the dataset to facilitate separate analysis of the maintenance history of the bridges scheduled for replacement and bridges flagged but not scheduled. This allowed additional review of maintenance history data, facilitated additional insight into the maintenance types most often reoccurring for scheduled and non-scheduled bridges, and the differences between the two sets of bridges.

For bridges scheduled for replacement, a total of 1,639 maintenance cases occurring on 499 bridges was analyzed. Summary tables of these analyses, similar to the one shown above (Table 4.1), are provided for both sets of bridges. A summary of analysis of reoccurring maintenance actions and costs for bridges scheduled for replacement is shown in Table 4.2, with additional information presented in the Appendix in Table A.2. Similarly, Figures 4.3 and 4.4 are identical to the Figure 4.1 and 4.2, but show the results of the analysis only using the data from the list of bridges scheduled for replacement.

Similarly, the dataset of maintenance actions for bridges flagged for replacement but not scheduled was analyzed. This dataset included a total of 848 maintenance cases for actions performed on 397 bridges. A summary table is presented in Table 4.3, with additional information provided in Appendix A (Table A.3). A summary of annual maintenance activities and annual costs associated with this subset of bridges is shown in Figures 4.5 and 4.6.

Key conclusions that can be drawn from this data are that for bridges scheduled for replacement, the most reoccurring maintenance action was repair and replace timber substructure components, with 6.21% of all scheduled bridges having reoccurring timber substructure maintenance. Maintenance actions associated with steel superstructure components are also a highly reoccurring maintenance action linked to current project prioritization, with 4.01% of all scheduled bridges experiencing this type of maintenance. Other maintenance types with high rates of reoccurrence which are linked to current bridge project prioritization include: maintain concrete superstructure components, repair bridge expansion joints, maintain timber deck, maintain concrete deck, and maintain timber wings and bulkheads. Analysis of maintenance history data for bridges flagged but not scheduled for replacement indicated that bridges have similar higher reoccurring cases as the scheduled bridges. However, unlike the findings for bridges scheduled for replacement, not all 20 maintenance types had a reoccurring case associated with bridges appearing in the flagged for replacement but not scheduled list of bridges. For example, the reoccurring maintenance action of repair timber substructure components is associated with 2.77% of this subset of bridges. However, there are no cases of maintain

/ repair steel substructure components in this list of reoccurring maintenance activities for these bridges in this list.

Table 4.2: Sample reoccurring maintenance action summary for bridges scheduled for replacement

Reoccurring Maintenance Factors for Bridges:	Number of Bridges with 2 or more cases of reoccurring (# of bridges)	Total Number of Reoccurring Cases	Percent of Bridges with reoccuring maintenance	Total Cost of Reoccurring Maintenance	Percent of reoccurring bridges to to Total # of bridges	Percent of Bridges with Maintenance Action Performed
Asphalt Pavement Repair and Patching	2	6	18.18%	$ 16,887.61	0.40%	2.20%
Maintain Timber Superstructure Components	9	20	28.13%	$ 337,800.16	1.80%	6.41%
Maintain Concrete Superstructure Components	11	23	18.97%	$ 394,863.77	2.20%	11.62%
Maintain/Repair Bridge Exp. Joint	12	25	21.05%	$ 87,840.13	2.40%	11.42%
Maintain Steel Superstructure Components	20	48	22.22%	$ 1,834,345.33	4.01%	18.04%
Maintain Timber Deck Components	11	30	27.50%	$ 391,190.36	2.20%	8.02%
Maintain Concrete Deck	14	51	23.33%	$ 771,927.63	2.81%	12.02%
Maintain/Repair/Replace Steel Plank Bridge Floor	2	6	22.22%	$ 78,243.31	0.40%	1.80%
Maintain Movable Bridges	1	12	33.33%	$ 550,669.58	0.20%	0.60%
Operations of Movable Bridges	1	6	100.00%	$ 1,412,547.93	0.20%	0.20%
Repair/Replace Timber Substructure Components	31	70	25.00%	$ 1,209,848.83	6.21%	24.85%
Repair/Maintain Timber Wings and Blkhds.	10	21	15.15%	$ 546,987.72	2.00%	13.23%
Maintain Concrete Substructure Components	8	16	14.55%	$ 240,029.41	1.60%	11.02%
Maintain Slope Protection	2	4	5.56%	$ 195,219.52	0.40%	7.21%
Maintain / Repair Steel Substructure Components	4	10	23.53%	$ 152,024.84	0.80%	3.41%
Maintenance and Repair of Fender System	1	3	50.00%	$ 139,327.47	0.20%	0.40%
Maintain Concrete Bridge Floor	1	2	7.69%	$ 10,600.96	0.20%	2.61%
Maintain Deck Expansion Joints	2	4	12.50%	$ 13,236.73	0.40%	3.21%
Maintain Timber Piles and Posts	1	2	11.11%	$ 38,979.71	0.20%	1.80%
Bridge Installation and Repair	1	2	50.00%	$ 106,566.17	0.11%	0.22%
Maintain Steel Plate Bridge Joint	1	2	50.00%	$ 5,342.38	0.11%	0.22%

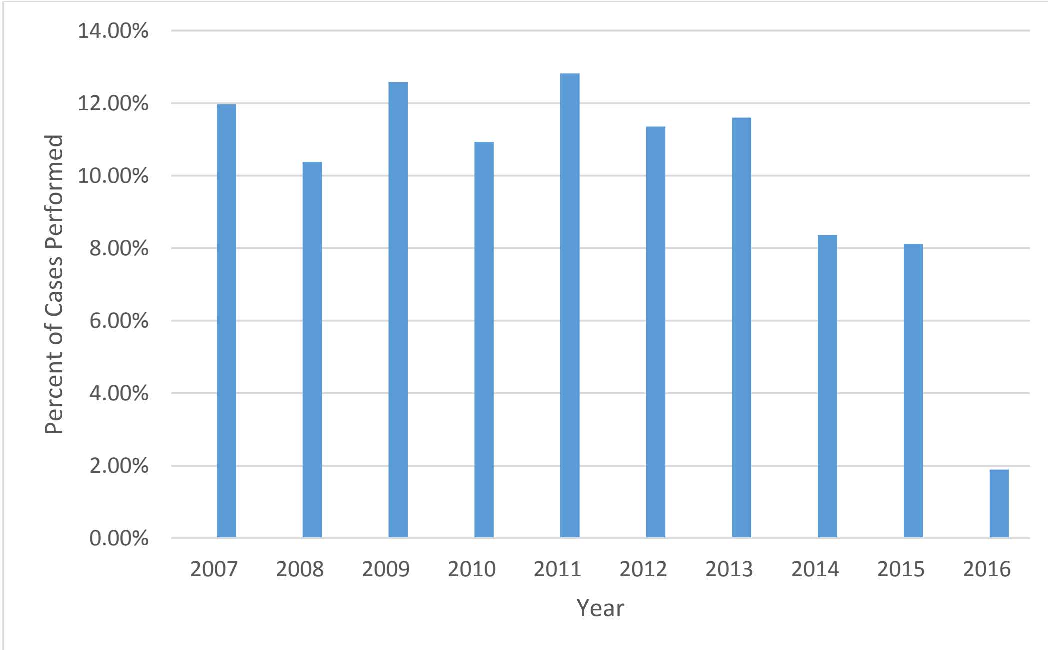


Figure 4.3: Percentage of maintenance work performed yearly for scheduled bridges

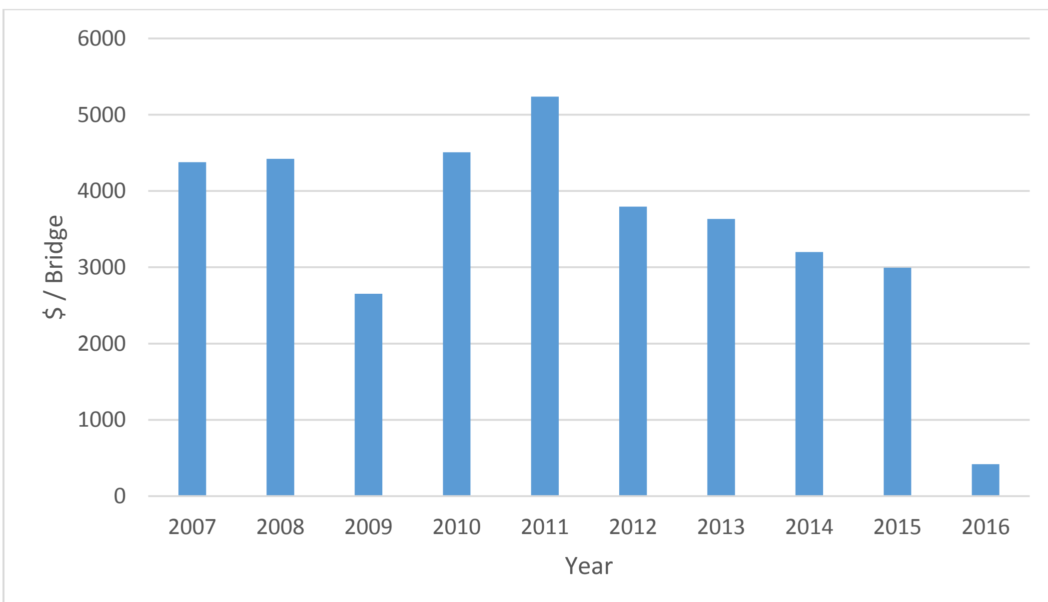


Figure 4.4: Average total cost of yearly maintenance per bridge for scheduled bridges

Table 4.3: Sample reoccurring maintenance action summary for bridges flagged but not scheduled for replacement

Reoccurring Maintenance Factors for Bridges:	Number of Bridges with 2 or more cases of reoccurring (# of bridges)	Total Number of Reoccurring Cases	Percent of Bridges with reoccuring maintenance	Total Cost of Reoccurring Maintenance	Percent of reoccurring bridges to to Total # of bridges	Percent of Bridges with Maintenance Action Performed
Asphalt Pavement Repair and Patching	0	0	0.00%	$ -	0.00%	0.00%
Maintain Timber Superstructure Components	1	3	4.00%	$ 38,441.82	0.25%	6.30%
Maintain Concrete Superstructure Components	2	4	33.33%	$ 16,145.88	0.50%	1.51%
Maintain/Repair Bridge Exp. Joint	1	2	14.29%	$ 44,106.43	0.25%	1.76%
Maintain Steel Superstructure Components	10	20	15.38%	$ 291,593.67	2.52%	16.37%
Maintain Timber Deck Components	11	30	18.64%	$ 192,451.24	2.77%	14.86%
Maintain Concrete Deck	2	5	25.00%	$ 10,690.77	0.50%	2.02%
Maintain/Repair/Replace Steel Plank Bridge Floor	2	7	33.33%	$ 18,241.63	0.50%	1.51%
Maintain Movable Bridges	0	0	0.00%	$ -	0.00%	0.00%
Operations of Movable Bridges	0	0	0.00%	$ -	0.00%	0.00%
Repair/Replace Timber Substructure Components	11	25	9.57%	$ 321,918.00	2.77%	28.97%
Repair/Maintain Timber Wings and Blkhds.	10	21	15.15%	$ 546,987.72	2.00%	16.62%
Maintain Concrete Substructure Components	0	0	0.00%	$ -	0.00%	0.00%
Maintain Slope Protection	0	0	0.00%	$ -	0.00%	0.00%
Maintain / Repair Steel Substructure Components	0	0	0.00%	$ -	0.00%	0.00%
Maintenance and Repair of Fender System	0	0	100.00%	$ -	0.00%	0.00%
Maintain Concrete Bridge Floor	0	0	200.00%	$ -	0.00%	0.00%
Maintain Deck Expansion Joints	0	0	300.00%	$ -	0.00%	0.00%
Maintain Timber Piles and Posts	0	0	400.00%	$ -	0.00%	0.00%
Bridge Installation and Repair	1	2	16.67%	$ 44,873.53	0.11%	0.67%
Maintain Steel Plate Bridge Joint	0	2	0.00%	$ -	0.00%	0.00%

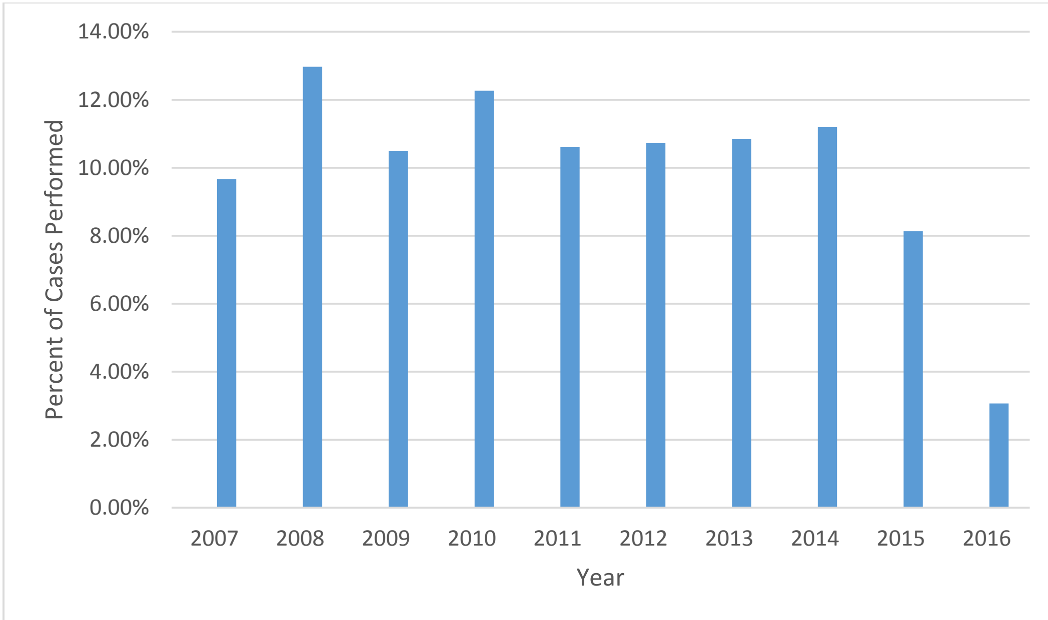


Figure 4.5: Percentage of maintenance work performed yearly for non-scheduled bridges

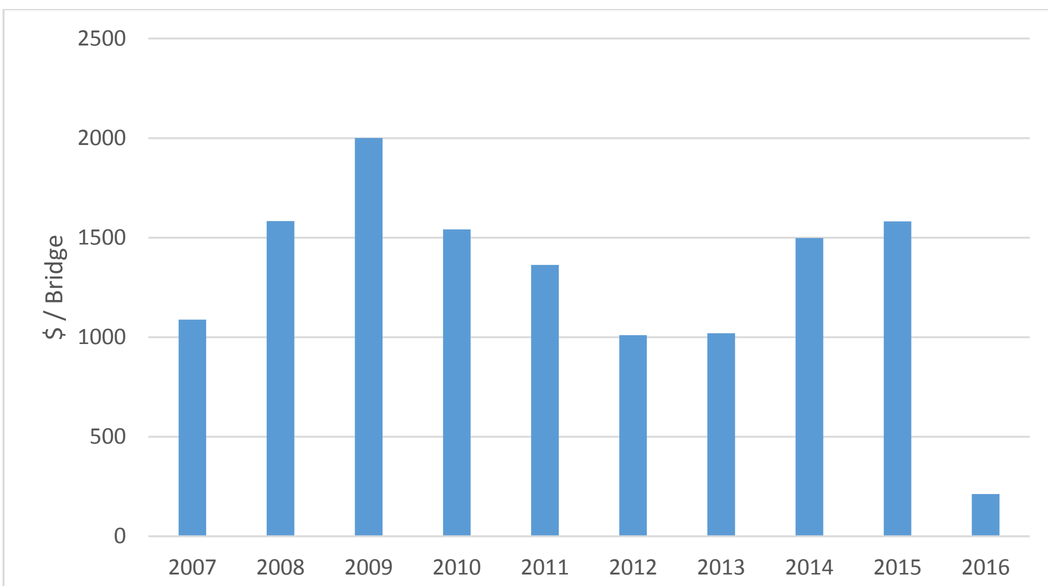


Figure 4.6: Average total cost of yearly maintenance per bridge for non-scheduled bridges

Although the most often reoccurring maintenance actions are similar for both scheduled bridges and flagged but not scheduled bridges, there is a significant difference in the amount of money spent on a particular maintenance action case between these two subsets of bridges. A histogram of the total costs of each maintenance action case is shown in Figure 4.7. In this histogram, it can be seen that cost per maintenance action tends to be higher for scheduled bridges than for bridges flagged as considered for replacement but not scheduled. It is important to note this difference because it validates that NCDOT is indeed selecting bridges for replacement that are associated with higher maintenance cost, thus justifying the desire of NCDOT to incorporate maintenance burden into the new bridge prioritization index.

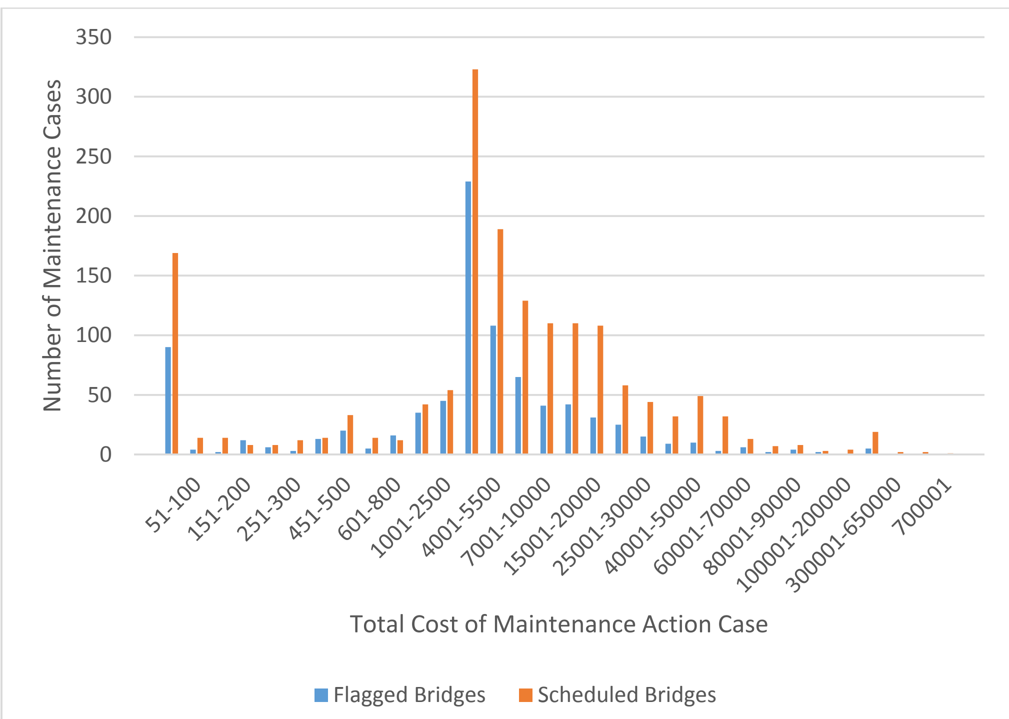


Figure 4.7: Total cost of maintenance action case over past 10 years for scheduled and flagged, but not scheduled bridges.

Using this same cost data, the average total maintenance cost per year for each bridge was determined. This was used to determine the reoccurring maintenance actions associated with bridges with the highest average yearly cost appearing on the scheduled for replacement list. For convenience, 30 bridges with the highest average yearly maintenance costs were identified. The total maintenance cost and average yearly cost associated with these bridges is shown in Table 4.4. It is noted that one bridge with one of the highest average yearly maintenance costs was a moveable bridge. Since this is not a common type of bridge, and often has costly mechanical systems that may influence maintenance cost, moveable bridges were removed from the dataset.

Review of maintenance cost data from the 30 bridges with the highest average annual maintenance cost allows conclusions to be developed for the other scheduled for replacement bridges. The main reoccurring maintenance actions for bridges of this subset included (as shown in Table 4.5):

- repair or replace timber substructure (with 5 bridges and 12 cases)
- maintain concrete deck (with 3 bridges and 17 cases)

Other reoccurring maintenance actions included:

- maintain timber superstructure components
- repair bridge expansion joints
- maintain steel superstructure components
- timber deck components
- timber wings and bulkheads
- timber piles and posts

Other maintenance types appearing in Table 4.1 did not have any reoccurring maintenance cases in the dataset for the 30 bridges with the highest average annual maintenance cost. Some maintenance types, such as asphalt pavement repair and patching, did not have any cases at all for this set of bridges, as shown in Table 4.5.

Table 4.4: Thirty bridges with the highest average annual maintenance cost

Bridge Number	Total Cost	Average Cost Per Year
640029	$ 412,121.28	$ 41,212.13
980035	$ 354,735.83	$ 35,473.58
570053	$ 254,584.22	$ 25,458.42
840105	$ 206,095.49	$ 20,609.55
410093	$ 205,894.60	$ 20,589.46
600100	$ 202,608.18	$ 20,260.82
350203	$ 196,995.92	$ 19,699.59
250060	$ 183,106.10	$ 18,310.61
710019	$ 169,290.12	$ 16,929.01
100370	$ 166,702.97	$ 16,670.30
720050	$ 166,109.03	$ 16,610.90
810018	$ 162,669.35	$ 16,266.94
220165	$ 157,656.46	$ 15,765.65
910494	$ 150,836.89	$ 15,083.69
810122	$ 147,905.26	$ 14,790.53
250045	$ 144,277.33	$ 14,427.73
480189	$ 141,968.18	$ 14,196.82
300045	$ 132,907.93	$ 13,290.79
460008	$ 129,235.89	$ 12,923.59
980010	$ 125,467.17	$ 12,546.72
600029	$ 125,408.62	$ 12,540.86
000173	$ 119,726.37	$ 11,972.64
720051	$ 117,562.43	$ 11,756.24
380096	$ 116,195.87	$ 11,619.59
180147	$ 114,256.13	$ 11,425.61
500216	$ 109,141.85	$ 10,914.19
910258	$ 108,691.43	$ 10,869.14
120132	$ 105,495.94	$ 10,549.59
250022	$ 105,129.66	$ 10,512.97
090040	$ 105,061.81	$ 10,506.18

Table 4.5: Reoccurring maintenance action summary for the thirty bridges with the highest average annual maintenance cost

Reoccurring Maintenance Factors:	Number of Bridges with 2 or more cases of reoccurring (# of bridges)	Total Number of Reoccurring Cases	Average Number of reoccurring cases per bridge	Total Number of Cases (Both reoccurring and non-reoccurring)	Percentage of Cases Reoccurring	Total Number of Bridges with the maintenance type	Percent of Bridges with reoccuring maintenance	Total Cost of Reoccurring Maintenance	Average Cost of Reoccuring Maintenance	Average Cost of Non-reoccruing Manitenance	Total Cost of all Maintenance
Repair/Replace Timber Substructure Components	5	12	2.40	16	75%	9	56%	$ 253,585.28	$ 21,132.11	$ 73,315.91	$ 546,848.92
Maintain Concrete Deck	3	17	5.67	21	81%	7	43%	$ 396,684.93	$ 23,334.41	$ 11,655.64	$ 443,307.50
Maintain Timber Superstructure Components	2	4	2.00	6	67%	4	50%	$ 101,516.44	$ 25,379.11	$ 71,191.54	$ 243,899.51
Maintain Steel Superstructure Components	2	6	3.00	13	46%	9	22%	$ 874,485.33	$ 145,747.56	$ 41,480.70	$ 1,164,850.25
Maintain Timber Deck Components	2	6	3.00	7	86%	3	67%	$ 167,800.34	$ 27,966.72	$ 291,019.67	$ 458,820.01
Maintain/Repair Bridge Exp. Joint	1	2	2.00	6	33%	5	20%	$ 9,453.82	$ 4,726.91	$ 152.22	$ 10,062.71
Repair/Maintain Timber Wings and Blkhds.	1	2	2.00	6	33%	5	20%	$ 206,328.39	$ 103,164.20	$ 15,000.88	$ 266,331.90
Maintain Timber Piles and Posts	1	2	2.00	3	67%	2	50%	$ 38,979.71	$ 19,489.86	$ 11,173.43	$ 50,153.14
Maintain Concrete Superstructure Components	0	0	0.00	1	0%	1	0%	$ -	$ -	$ 143,680.19	$ 143,680.19
Maintain/Repair/Replace Steel Plank Bridge Floor	0	0	0.00	0	0%	0	0%	$ -	$ -	$ -	$ -
Maintain Movable Bridges	0	0	0.00	0	0%	0	0%	$ -	$ -	$ -	$ -
Operations of Movable Bridges	0	0	0.00	0	0%	0	0%	$ -	$ -	$ -	$ -
Maintain Concrete Substructure Components	0	0	0.00	2	0%	2	0%	$ -	$ -	$ 67,366.92	$ 134,733.83
Maintain Slope Protection	0	0	0.00	3	0%	3	0%	$ -	$ -	$ 57,836.19	$ 173,508.56
Maintain / Repair Steel Substructure Components	0	0	0.00	2	0%	2	0%	$ -	$ -	$ 140,669.37	$ 281,338.73
Maintenance and Repair of Fender System	0	0	0.00	1	0%	1	0%	$ -	$ -	$ 337.50	$ 337.50
Maintain Concrete Bridge Floor	0	0	0.00	1	0%	1	0%	$ -	$ -	$ 16,459.64	$ 16,459.64
Maintain Deck Expansion Joints	0	0	0.00	2	0%	2	0%	$ -	$ -	$ 4,118.18	$ 8,236.36
Asphalt Pavement Repair and Patching	0	0	0.00	0	0%	0	0%	$ -	$ -	$ -	$ -

A significant finding of this analysis is that over the past 10 years, there has been a large difference between the funds spent on maintenance actions for bridges scheduled for replacement, and bridges flagged but not scheduled for replacement. This difference is illustrated in cumulative distribution charts, shown in Figure 4.8 and 4.9, which show the total amount spent on maintenance actions (Figure 4.8) and the total amount spent on just reoccurring maintenance actions (Figure 4.9) over the past 10 years. These plots demonstrate that bridges that have been selected for replacement have accumulated both higher total cost and higher cost for reoccurring maintenance actions over the past 10 years. During this same timeframe bridges flagged for replacement but not scheduled exhibit a lower total cost for reoccurring maintenance. Additionally, 90% of the maintenance action they have received are under $1,000 per year on average, far lower than the average cost of typical maintenance actions on bridges scheduled for replacement at approximately $2,500 per year.

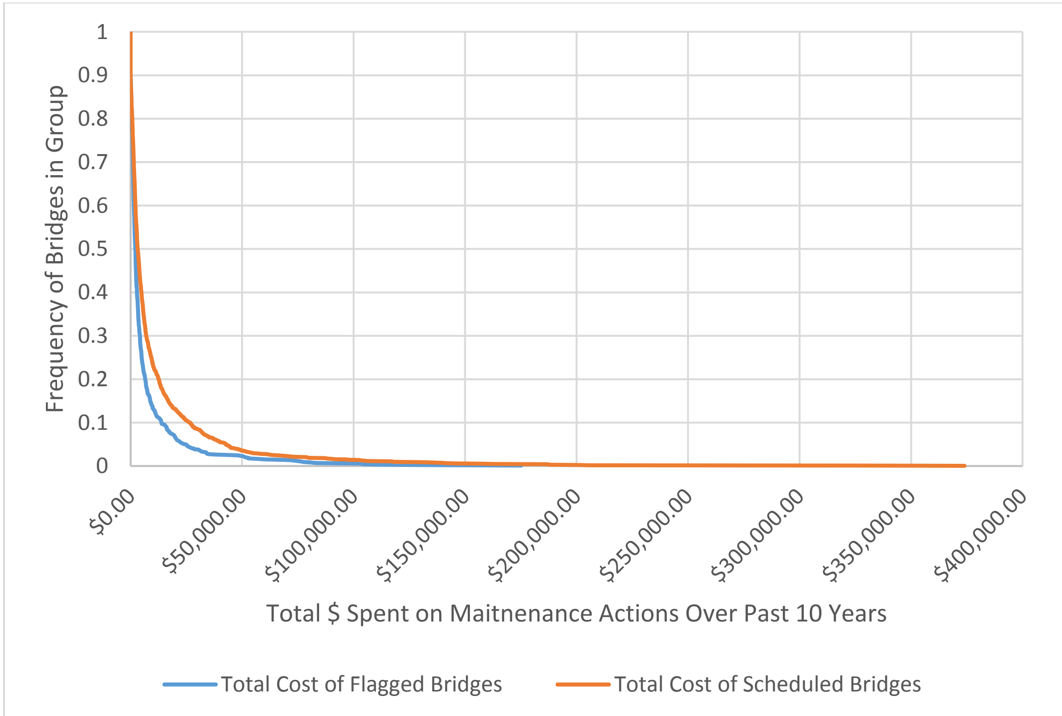


Figure 4.8: Cumulative distribution of scheduled and flagged bridges historical total maintenance cost over the past 10 years

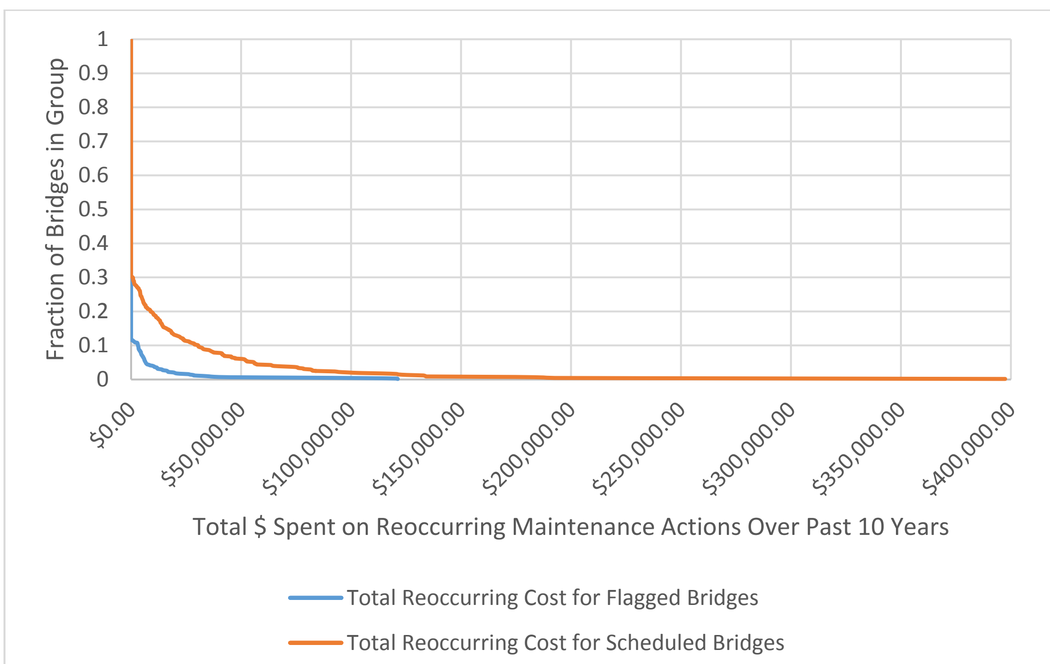


Figure 4.9: Cumulative distribution of scheduled and flagged bridges historical total reoccurring maintenance cost over the past 10 years

To facilitate a yearly comparison of maintenance costs, average yearly costs were converted to Net Present Value (NPV) using the appropriate cost index for each year (CPI Inflation Rates, 2016). As shown in Figures 4.10 and 4.11, the average yearly cost of maintenance for bridges scheduled and flagged for replacement are significantly different. In Figure 4.10, it can be seen that bridges currently scheduled for maintenance have a higher average yearly cost (typically less than half) than those bridges that are flagged for replacement but not scheduled. In Figure 4.11, it is shown that about 50% of the average total cost spent on bridge maintenance over the past 10 years are reoccurring cost. Overall, this analysis justifies use of maintenance history as a performance criteria in a new project prioritization index.

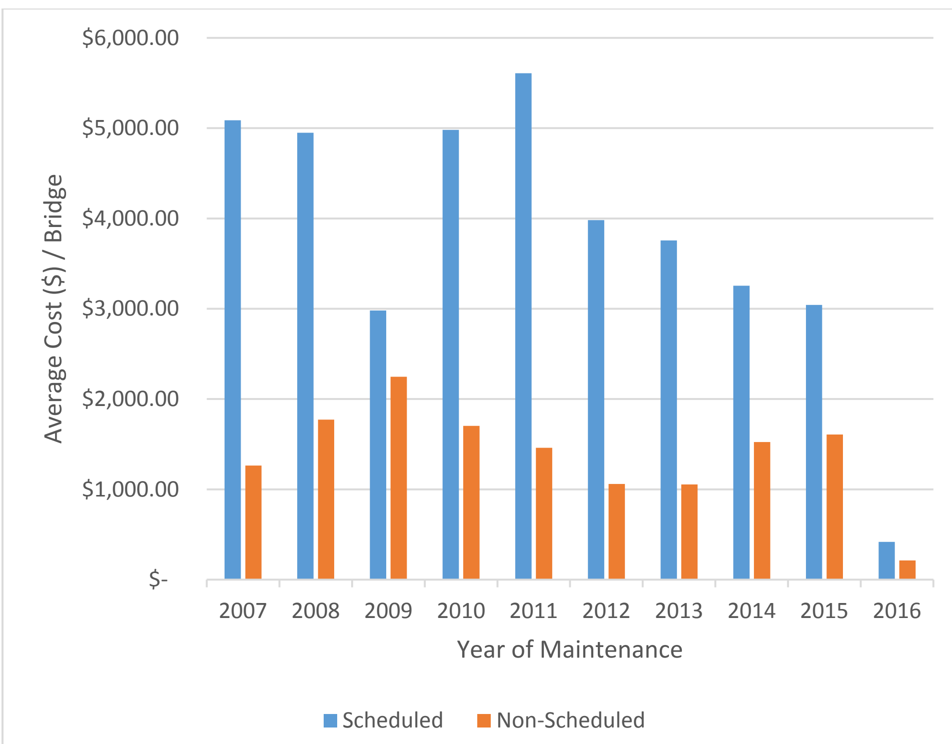


Figure 4.10: Average historical data total maintenance cost per bridge per year for scheduled and flagged bridges over past 10 years

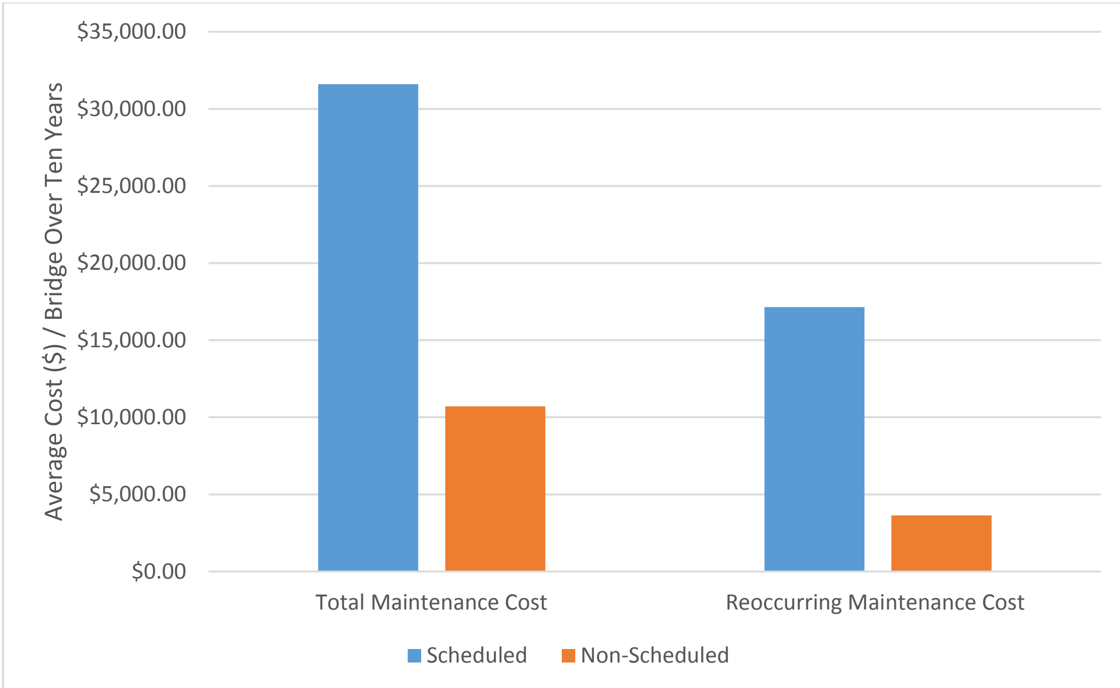


Figure 4.11 Average historical data total maintenance cost over past 10 years for total maintenance cost and reoccurring maintenance cost of scheduled and flagged bridge

4.2 Maintenance Needs

In addition to the history of maintenance performed on bridges (maintenance burden), NCDOT also desires that inspector recommended maintenance needs should also contribute to the new proposed bridge prioritization index. If a particular bridge is in need of significant maintenance, it is possible that replacing the bridge is more cost effective than spending money on maintaining it. The quantities and unit costs reflected in the maintenance needs also may better reflect the severity of the current deterioration better than the general condition rating since inspection recommended maintenance needs are developed from element-level condition ratings. Incorporation of inspector recommended maintenance needs into a new prioritization index should become increasingly useful as NCDOT continues to gather element-based inspection data, a recent change in inspection protocol.

4.2.1 Sources of Maintenance Needs Data

Similar to the procedure utilized for the maintenance burden data, maintenance actions for bridges included in the BMIP plan (scheduled for replacement) and flagged for replacement but not scheduled were utilized in this analysis. The maintenance needs data was extracted from NCDOT's BMS, and was categorized into two datasets: priority maintenance needs and recommended maintenance needs, as noted by the inspector and recorded in the BMS. Each maintenance need was linked to a bridge ID and NCDOT district. Other information associated with each recorded maintenance need included type of maintenance action needed, quantity, deck width, and deck length. An analysis was performed to determine the maintenance actions that are most common among the inspector recommended maintenance needs, the total cost of each maintenance type, and identify other useful trends.

4.2.2 Preparation of Dataset for Analysis

Inspector recommended maintenance needs for bridges included 32 individual maintenance actions, some which could reasonably be linked to prioritization for replacement (maintain concrete superstructure components) and others that likely would not be as influential in prioritization for replacement (such as maintain handrails). The dataset included 9,184 maintenance need cases associated with a total of 1,453 bridges. During initial analysis of the maintenance needs data, all types of maintenance needs were allowed to remain in the dataset. However, records for maintenance needs not clearly linked to prioritized bridges were removed from the dataset once trends linking specific maintenance needs to these bridges were identified.

4.2.3 Analytical Approach

The main goal of this analysis of maintenance needs was to determine which maintenance actions were the most prevalent in the current needs for bridges across the state. This process included organizing the data by bridges scheduled for replacement and bridges flagged for replacement but not scheduled, similar to the approach utilized to evaluate maintenance burden data. For inspector recommended maintenance needs, there are two other subcategories, priority maintenance and recommended maintenance. In Figure 4.12, the organization of data this analysis is illustrated. To assist in determining the most prevalent maintenance needs, the total number of cases and associated quantities were defined for bridges scheduled for replacement, as well as bridges flagged but not scheduled for replacement, as sorted by priority and recommended maintenance. Additional analysis was performed to evaluate the costs associated with maintenance needs for previously prioritized bridges. To accomplish this, the average and total costs were computed for each maintenance need type, for bridges categorized as shown in Table 4.6. More detailed information describing this analysis is presented in the next section.

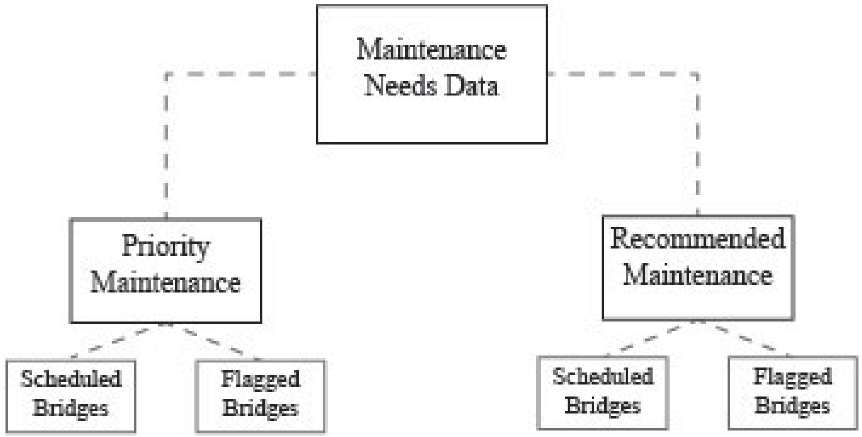


Figure 4.12: Maintenance need organization diagram

4.2.4 Analysis Methodology and Results

Initially, all of the maintenance need records were identified and the total cases, quantities, average cost, and total cost were listed, shown in Table 4.6. The highlighted areas in Table 4.6 identify the largest number of cases, quantities of needed work, and total cost. The maintenance need of “maintain concrete substructure components” has the largest number of cases listed in the maintenance needs database at 10,178 cases for the 5-year analysis period, while the maintenance need of “maintain concrete deck” has both largest total quantity (17,636,550 square feet) and total cost (projected as $444,441,060).

Table 4.6: Summary of priority and recommended maintenance needs identified by inspectors

Maintenance Number	Maintenance Type	Number of Cases	Total Quantities	Average Cost	Total Cost
3304	Maintain/Replace Timber Superstructure Components	1,222	163,645	$111.58	$18,259,509.10
3306	Maintain Concrete Superstructure Components	5,879	337,502	$132.19	$44,614,389.38
3308	Maint. Of Steel Plate Bridge Joints	772	41,304	$114.80	$4,741,699.20
3310	Maintenance/Repair/Replacement of Standard Bridge Expansion Joints	7,009	270,321	$23.60	$6,379,575.60
3312	Maint/Replace/Repair Modular Bridge Joints	120	11,137	$125.56	$1,398,361.72
3314	Maintain Steel Superstructure Components	6,714	1,471,842	$196.60	$289,364,137.20
3316	Maint to Timber Handrail	2,496	63,884	$12.41	$792,800.44
3318	Maint to Concrete Handrail	8,057	907,952	$192.05	$174,372,181.60
3320	Maint to Aluminum Handrail	42	1,631	$84.58	$137,949.98
3322	Maint to Steel Handrail	2,338	69,114	$39.90	$2,757,648.60
3324	Maint / Repair / Replace Timber Deck Components	2,752	327,928	$36.29	$11,900,507.12
3326	Maintain Concrete Deck	9,339	17,636,550	$25.20	$444,441,060.00
3328	Maintenance/Repair/ Replace Steel Plank Bridge Floor	683	198,820	$56.64	$11,261,164.80
3330	Maintenance/Repair Open Grid Steel Floor	5	157	$102.94	$16,161.58
3332	Maint Drainage System - Bridge	76	4,222	$2.42	$10,217.24
3334	Bridge Bearings	10,046	92,355	$218.46	$20,175,873.30
3336	Moveable Bridges (Maintenance)	9	782	$40.20	$31,436.40
3342	Clean and Paint Structural Steel	9,996	8,389,325	$7.18	$60,235,353.50
3344	Repair / Replace Timber Substructure Components	3,659	97,387	$214.70	$20,908,988.90
3346	Repair / Maintain Timber Wings & Blkhds	3,130	111,671	$41.31	$4,613,129.01
3348	Maintain Concrete Substructure Components	10,178	385,555	$209.91	$80,931,850.05
3350	Maint R C Wings and Walls	7,659	110,296	$121.50	$13,400,964.00
3352	Maint Slope Protection	551	83,882	$14.89	$1,249,002.98
3354	Maintain Steel Substructure Components	5,954	72,083	$273.54	$19,717,583.82
3362	Maintenance and Repair of Fender System	8	2,911	$113.06	$329,117.66
3364	Replace / Construct Fender System	1	500	$94.38	$47,190.00
3366	Drift and Debris Removal	768	25,872	$40.60	$1,050,403.20
3368	Installation and Replacement of NBIS Pipes and Culverts	20	1,301	$469.04	$610,221.04
3370	Maintenance and Repair of NBIS Pipes and Culverts	4,694	391,639	$250.05	$97,929,331.95
3372	Bridge Installation & Replacement	1	3	$56.53	$169.59
3374	Repair and Maint of Pedestrian Bridges	14	1,299	$35.12	$45,620.88
3376	Clean/Wash Bridge Decks	686	225,949	$0.05	$11,297.45
	Totals	104,878	31,498,819	$108.04	$1,331,734,897.29

As stated previously, the maintenance needs data was divided into a set of subcategories, shown in Figure 4.12. The list of priority were extracted from the NCDOT's BMS maintenance data, the BMPbaseline plan, and the BMPdynamic plan, For both sets of bridges (scheduled for replacement and bridges flagged but not scheduled for replacement), the total number of cases and total quantities were computed for each priority maintenance need action. This same process was also repeated for all recommended maintenance needs actions. The database consists of 9,184 maintenance need cases for a total of 1,453 bridges. Of that, 683 are bridges scheduled for replacement, with 453 of those bridges having no priority maintenance needs, and 1 bridge having no recommended maintenance needs. There are 770 bridges flagged but not scheduled for replacement, with 579 of those having no priority maintenance needs, and 31 having no recommended maintenance needs. In Table 4.7, the data for priority maintenance needs is displayed, and in Table 4.8, the data for recommended maintenance needs is shown.

The first conclusion drawn from this data is that the major maintenance needs actions for both sets of bridges (bridges scheduled for replacement and bridges flagged for replacement but not scheduled) are similar. For example, the maintenance action with the most cases under scheduled bridges is maintain steel superstructure components, with 74 cases. This is the second highest maintenance action for bridges flagged for replacement but not scheduled, which has 65 cases. Repair/replace timber substructure components is the maintenance need with the highest number of cases for bridges flagged but not scheduled for replacement. This maintenance need is the second most prevalent for bridges scheduled for replacement with 64 cases.

Table: 4.7 Priority maintenance needs

Maintenance Number	Maintenance Type	Scheduled Bridges: Number of Cases	Scheduled Bridges: Quantities	Flagged, but not Scheduled: Number of Cases	Flagged, but not Scheduled: Quantities	Sum
3314	Maintain Steel Superstructure Components	74	3492	65	3103	139
3344	Repair / Replace Timber Substructure Components	64	1166	75	982	139
3306	Maintain Concrete Superstructure Components	49	4103	7	550	56
3348	Maintain Concrete Substructure Components	40	1247	5	146	45
3326	Maintain Concrete Deck	22	450	2	120	24
3354	Maintain Steel Substructure Components	16	1809	0	0	16
3346	Repair / Maintain Timber Wings & Blkhds	14	306	36	2259	50
3304	Maintain/Replace Timber Superstructure Components	10	176	24	967	34
3322	Maint to Steel Handrail	8	99	1	15	9
3352	Maint Slope Protection	8	672	12	554	20
3366	Drift and Debris Removal	8	426	4	176	12
3316	Maint to Timber Handrail	5	172	16	371	21
3334	Bridge Bearings	5	35	1	1	6
3318	Maint to Concrete Handrail	4	35	2	121	6
3324	Maint / Repair / Replace Timber Deck Components	4	3314	17	2048	21
3328	Maintenance/Repair/ Replace Steel Plank Bridge Floor	1	2	0	0	1
3308	Maint. Of Steel Plate Bridge Joints	0	0	0	0	-
3310	Maintenance/Repair/Replacement of Standard Bridge Expansion Joints	0	0	0	0	-
3312	Maint/Replace/Repair Modular Bridge Joints	0	0	0	0	-
3320	Maint to Aluminum Handrail	0	0	0	0	-
3330	Maintenance/Repair Open Grid Steel Floor	0	0	0	0	-
3332	Maint Drainage System - Bridge	0	0	0	0	-
3336	Moveable Bridges (Maintenance)	0	0	0	0	-
3342	Clean and Paint Structural Steel	0	0	0	0	-
3350	Maint R C Wings and Walls	0	0	0	0	-
3362	Maintenance and Repair of Fender System	0	0	0	0	-
3364	Replace / Construct Fender System	0	0	0	0	-
3368	Installation and Replacement of NBIS Pipes and Culverts	0	0	0	0	-
3370	Maintenance and Repair of NBIS Pipes and Culverts	0	0	0	0	-
3372	Bridge Installation & Replacement	0	0	0	0	-
3374	Repair and Maint of Pedestrian Bridges	0	0	0	0	-
3376	Clean/Wash Bridge Decks	0	0	0	0	-
	Totals	332	17504	267	11,413	

Table: 4.8 Recommended maintenance needs

Maintenance Number	Maintenance Type	Scheduled: Number of Cases	Scheduled: Quantities	Flagged, but not scheduled: Number of Cases	Flagged, but not scheduled: Quantities	Sum
3342	Clean and Paint Structural Steel	504	674199	438	500740	942
3348	Maintain Concrete Substructure Components	419	26374	237	4443	656
3344	Repair / Replace Timber Substructure Components	405	18085	496	10679	901
3334	Bridge Bearings	404	10007	344	4144	748
3326	Maintain Concrete Deck	399	481800	141	89002	540
3314	Maintain Steel Superstructure Components	367	162771	428	119930	795
3346	Repair / Maintain Timber Wings & Blkhds	313	9512	442	15672	755
3318	Maint to Concrete Handrail	255	25574	115	3100	370
3310	Maintenance/Repair/Replacement of Standard Bridge Expansion Joints	252	7513	58	1262	310
3350	Maint R C Wings and Walls	251	6016	206	3974	457
3322	Maint to Steel Handrail	214	11676	59	2628	273
3306	Maintain Concrete Superstructure Components	204	25618	73	3066	277
3324	Maint / Repair / Replace Timber Deck Components	186	25817	504	59454	690
3354	Maintain Steel Substructure Components	181	6089	67	1133	248
3316	Maint to Timber Handrail	166	7775	513	12360	679
3304	Maintain/Replace Timber Superstructure Components	80	28742	217	17959	297
3328	Maintenance/Repair/ Replace Steel Plank Bridge Floor	44	33797	20	7151	64
3376	Clean/Wash Bridge Decks	27	7833	45	7677	72
3366	Drift and Debris Removal	21	1177	21	219	42
3352	Maint Slope Protection	14	3038	22	2589	36
3332	Maint Drainage System - Bridge	5	158	4	335	9
3308	Maint. Of Steel Plate Bridge Joints	2	124	0	0	2
3312	Maint/Replace/Repair Modular Bridge Joints	1	6	0	0	1
3330	Maintenance/Repair Open Grid Steel Floor	1	1	0	0	1
3320	Maint to Aluminum Handrail	0	0	0	0	0
3336	Moveable Bridges (Maintenance)	0	0	0	0	0
3362	Maintenance and Repair of Fender System	0	0	0	0	0
3364	Replace / Construct Fender System	0	0	0	0	0
3368	Installation and Replacement of NBIS Pipes and Culverts	0	0	0	0	0
3370	Maintenance and Repair of NBIS Pipes and Culverts	0	0	19	126	19
3372	Bridge Installation & Replacement	0	0	0	0	0
3374	Repair and Maint of Pedestrian Bridges	0	0	0	0	0
	Totals	4,715	1573702	4,469	867,643	

Another analysis approach utilized to determine the priority maintenance actions most prevalent among these prioritized sets of bridges was to normalize the data. To normalize the data, each case was divided by the total number of bridges, shown in Table 4.9. For example, using the maintenance need maintain steel super structure components under bridges scheduled for replacement:

$$74 / 1453 = 0.0509 \text{ or } 5.09\%$$

In Table 4.9, not only are the normalized bridge cases shown, but the data was also sorted to show the most significant maintenance needs types at the top of the table. Overall, the findings show that for bridges both scheduled for replacement and bridges flagged but not scheduled for replacement, the following priority maintenance actions are the most prevalent:

- Maintain steel superstructure components
- Repair / replace timber substructure components
- Maintain concrete superstructure components
- Maintain concrete substructure components, and
- Maintain concrete deck

Table 4.9: Normalized priority maintenance needs actions to total maintenance needs actions for bridges scheduled for replacement and flagged, but not scheduled

		Scheduled Bridges		Flagged, but not Scheduled	
Maintenance Number	Maintenance Type	Number of Cases	Quantities	Number of Cases	Quantities
3314	Maintain Steel Superstructure Components	5.09%	3492	4.47%	3103
3344	Repair / Replace Timber Substructure Components	4.40%	1166	5.16%	982
3306	Maintain Concrete Superstructure Components	3.37%	4103	0.48%	550
3348	Maintain Concrete Substructure Components	2.75%	1247	0.34%	146
3326	Maintain Concrete Deck	1.51%	450	0.14%	120
3354	Maintain Steel Substructure Components	1.10%	1809	0.00%	0
3346	Repair / Maintain Timber Wings & Blkhds	0.96%	306	2.48%	2259
3304	Maintain/Replace Timber Superstructure Components	0.69%	176	1.65%	967
3322	Maint to Steel Handrail	0.55%	99	0.07%	15
3352	Maint Slope Protection	0.55%	672	0.83%	554
3366	Drift and Debris Removal	0.55%	426	0.28%	176
3316	Maint to Timber Handrail	0.34%	172	1.10%	371
3334	Bridge Bearings	0.34%	35	0.07%	1
3318	Maint to Concrete Handrail	0.28%	35	0.14%	121
3324	Maint / Repair / Replace Timber Deck Components	0.28%	3314	1.17%	2048
3328	Maintenance/Repair/ Replace Steel Plank Bridge Floor	0.07%	2	0.00%	0
3308	Maint. Of Steel Plate Bridge Joints	0.00%	0	0.00%	0
3310	Maintenance/Repair/Replacement of Standard Bridge Expansion Joints	0.00%	0	0.00%	0
3312	Maint/Replace/Repair Modular Bridge Joints	0.00%	0	0.00%	0
3320	Maint to Aluminum Handrail	0.00%	0	0.00%	0
3330	Maintenance/Repair Open Grid Steel Floor	0.00%	0	0.00%	0
3332	Maint Drainage System - Bridge	0.00%	0	0.00%	0
3336	Moveable Bridges (Maintenance)	0.00%	0	0.00%	0
3342	Clean and Paint Structural Steel	0.00%	0	0.00%	0
3350	Maint R C Wings and Walls	0.00%	0	0.00%	0
3362	Maintenance and Repair of Fender System	0.00%	0	0.00%	0
3364	Replace / Construct Fender System	0.00%	0	0.00%	0
3368	Installation and Replacement of NBIS Pipes and Culverts	0.00%	0	0.00%	0
3370	Maintenance and Repair of NBIS Pipes and Culverts	0.00%	0	0.00%	0
3372	Bridge Installation & Replacement	0.00%	0	0.00%	0
3374	Repair and Maint of Pedestrian Bridges	0.00%	0	0.00%	0
3376	Clean/Wash Bridge Decks	0.00%	0	0.00%	0
	Totals	23%	17504	18%	11,413

Using the information gathered from the count and quantity data, cost information tables were created to examine the amount of funds being spent on each individual maintenance type. These tables include: maintenance number, number of cases, quantities, average cost, total area or linear footage, total cost by quantity, and measurement type. A summary of how these computations were performed is shown in Table 4.10. Following this approach, a table was created for both priority and recommended maintenance for bridges scheduled for replacement and bridges flagged for replacement but not scheduled. In Table 4.11, a cost summary for priority maintenance needs for bridges scheduled for replacement is shown. In Table 4.12, a cost summary for recommended maintenance needs for bridges scheduled for replacement is shown. Similar tables showing this analysis for bridges flagged for replacement but not scheduled, can be found in Appendix A (Table A.4, Table A.5).

Table 4.10: Cost data example table

Maintenance Number	**Number of Cases**	**Quantities**	**Average Cost**	**Total Area or LF**	**Total Cost by Quantity**
Example: 3304	Total # of bridges with this maintenance need	Sum of all the quantities for each case	Average cost of the maintenance type	The sum of each cases area or linear footage	The total quantity multiplied by the average cost

The cost data tables showed similarities to the count and quantity tables. The highest total cost was associated with the same maintenance needs actions that had the highest number of cases, which is expected due to the fact that the cost is found by multiplying the quantities times the average cost. For example, under scheduled bridges priority maintenance needs, “maintain steel superstructure components” had 74 cases, a total quantity of 3,492 linear feet and a total cost of $686,527.20, when an average cost of $196.60 per square foot was utilized. However, under the recommended maintenance for scheduled bridges, the maintenance need of “clean and paint steel structure” had the highest number of cases, but due to a low average cost of $7.18 per square foot, this type of maintenance need did not have the highest total cost by quantity.

Table 4.11: Cost data of priority maintenance for bridges scheduled for replacement

	Priority Maintenance					
Maintenance Number	Maintenance Type	Number of Cases	Quantities	Average Cost	Total Area or LF	Total Cost By Quantity
3304	Maintain/Replace Timber Superstructure Components	10	176.00	$ 111.58	819.00	$19,638.08
3306	Maintain Concrete Superstructure Components	49	4,103.00	$ 132.19	220,218.16	$542,375.57
3308	Maint. Of Steel Plate Bridge Joints	-	-	$ 114.80	-	$0.00
3310	Maintenance/Repair/Replacement of Standard Bridge Expansion Joints	-	-	$ 23.60	-	$0.00
3312	Maint/Replace/Repair Modular Bridge Joints	-	-	$ 125.56	-	$0.00
3314	Maintain Steel Superstructure Components	74	3,492.00	$ 196.60	385,600.81	$686,527.20
3316	Maint to Timber Handrail	5	172.00	$ 12.41	348.00	$2,134.52
3318	Maint to Concrete Handrail	4	35.00	$ 192.05	1,020.00	$6,721.75
3320	Maint to Aluminum Handrail	-	-	$ 84.58	-	$0.00
3322	Maint to Steel Handrail	8	99.00	$ 39.90	1,402.00	$3,950.10
3324	Maint / Repair / Replace Timber Deck Components	4	3,314.00	$ 36.29	8,276.38	$120,265.06
3326	Maintain Concrete Deck	22	450.00	$ 25.20	121,760.05	$11,340.00
3328	Maintenance/Repair/ Replace Steel Plank Bridge Floor	1	2.00	$ 56.64	779.22	$113.28
3330	Maintenance/Repair Open Grid Steel Floor	-	-	$ 102.94	-	$0.00
3332	Maint Drainage System - Bridge	-	-	$ 2.42	-	$0.00
3334	Bridge Bearings	5	35.00	$ 218.46	35.00	$7,646.10
3336	Moveable Bridges (Maintenance)	-	-	$ 40.20	-	$0.00
3342	Clean and Paint Structural Steel	-	-	$ 7.18	-	$0.00
3344	Repair / Replace Timber Substructure Components	64	1,166.00	$ 214.70	6,195.00	$250,340.20
3346	Repair / Maintain Timber Wings & Blkhds	14	306.00	$ 41.31	18,931.45	$12,640.86
3348	Maintain Concrete Substructure Components	40	1,247.00	$ 209.91	11,152.00	$261,757.77
3350	Maint R C Wings and Walls	-	-	$ 121.50	-	$0.00
3352	Maint Slope Protection	8	672.00	$ 14.89	20,914.92	$10,006.08
3354	Maintain Steel Substructure Components	16	1,809.00	$ 273.54	1,823.00	$494,833.86
3362	Maintenance and Repair of Fender System	-	-	$ 113.06	-	$0.00
3364	Replace / Construct Fender System	-	-	$ 94.38	-	$0.00
3366	Drift and Debris Removal	8	426.00	$ 40.60	426.00	$17,295.60
3368	Installation and Replacement of NBIS Pipes and Culverts	-	-	$ 469.04	-	$0.00
3370	Maintenance and Repair of NBIS Pipes and Culverts	-	-	$ 250.05	-	$0.00
3372	Bridge Installation & Replacement	-	-	$ 56.53	-	$0.00
3374	Repair and Maint of Pedestrian Bridges	-	-	$ 35.12	-	$0.00
3376	Clean/Wash Bridge Decks	-	-	$ 0.05	-	$0.00
	Total	**332**	**17,504.00**		**799,700.98**	**$ 2,447,586.03**
					Normilized Cost	**$ 3,583.58**

Table 4.12: Cost data of recommended maintenance for bridges scheduled for replacement

	Recommended Maintenance					
Maintenance Number	Maintenance Type	Number of Cases	Quantities	Average Cost	Total Area or LF	Total Cost By Quantity
3304	Maintain/Replace Timber Superstructure Components	80	28742	$ 111.58	6,158.00	$3,207,032.36
3306	Maintain Concrete Superstructure Components	204	25618	$ 132.19	953,397.17	$3,386,443.42
3308	Maint. Of Steel Plate Bridge Joints	2	124	$ 114.80	689.00	$14,235.20
3310	Maintenance/Repair/Replacement of Standard Bridge Expansion Joints	252	7513	$ 23.60	43,459.00	$177,306.80
3312	Maint/Replace/Repair Modular Bridge Joints	1	6	$ 125.56	105.00	$753.36
3314	Maintain Steel Superstructure Components	367	162771	$ 196.60	1,452,946.90	$32,000,778.60
3316	Maint to Timber Handrail	166	7775	$ 12.41	10,011.00	$96,487.75
3318	Maint to Concrete Handrail	255	25574	$ 192.05	47,248.00	$4,922,995.00
3320	Maint to Aluminum Handrail	-	0	$ 84.58	-	$0.00
3322	Maint to Steel Handrail	214	11676	$ 39.90	23,778.00	$465,872.40
3324	Maint / Repair / Replace Timber Deck Components	186	25817	$ 36.29	239,305.08	$936,898.93
3326	Maintain Concrete Deck	399	481800	$ 25.20	1,968,709.02	$12,141,360.00
3328	Maintenance/Repair/ Replace Steel Plank Bridge Floor	44	33797	$ 56.64	162,973.81	$1,914,262.08
3330	Maintenance/Repair Open Grid Steel Floor	1	1	$ 102.94	15,047.50	$102.94
3332	Maint Drainage System - Bridge	5	158	$ 2.42	559.00	$382.36
3334	Bridge Bearings	404	10007	$ 218.46	10,007.00	$2,186,129.22
3336	Moveable Bridges (Maintenance)	-	0	$ 40.20	-	$0.00
3342	Clean and Paint Structural Steel	504	674199	$ 7.18	1,886,270.17	$4,840,748.82
3344	Repair / Replace Timber Substructure Components	405	18085	$ 214.70	34,731.00	$3,882,849.50
3346	Repair / Maintain Timber Wings & Blkhds	313	9512	$ 41.31	591,004.51	$392,940.72
3348	Maintain Concrete Substructure Components	419	26374	$ 209.91	64,730.00	$5,536,166.34
3350	Maint R C Wings and Walls	251	6016	$ 121.50	1,403,360.82	#VALUE!
3352	Maint Slope Protection	14	3038	$ 14.89	31,879.79	$45,235.82
3354	Maintain Steel Substructure Components	181	6089	$ 273.54	26,746.00	$1,665,585.06
3362	Maintenance and Repair of Fender System	-	0	$ 113.06	-	$0.00
3364	Replace / Construct Fender System	-	0	$ 94.38	-	$0.00
3366	Drift and Debris Removal	21	1177	$ 40.60	1,177.00	$47,786.20
3368	Installation and Replacement of NBIS Pipes and Culverts	-	0	$ 469.04	-	$0.00
3370	Maintenance and Repair of NBIS Pipes and Culverts	-	0	$ 250.05	-	$0.00
3372	Bridge Installation & Replacement	-	0	$ 56.53	-	$0.00
3374	Repair and Maint of Pedestrian Bridges	-	0	$ 35.12	-	$0.00
3376	Clean/Wash Bridge Decks	27	7833	$ 0.05	54,198.19	$391.65
	Total	**4,715**	**1,573,702.00**		**9,028,490.97**	**$78,423,102.53**
					Normilized Cost	**$ 114,821.53**

It is clear from the summary tables presented above, that there is a larger cost associated with of recommended maintenance needs than with priority maintenance needs. As shown in Figure 4.13, recommended maintenance needs cases for both bridges scheduled for replacement and bridges flagged for replacement but not scheduled, have a higher percentage of cases with costs ranging over a larger scale. Priority maintenance needs are largely between $400 and $4,000 per case, and overall there are fewer total number of cases compared to recommended maintenance actions.

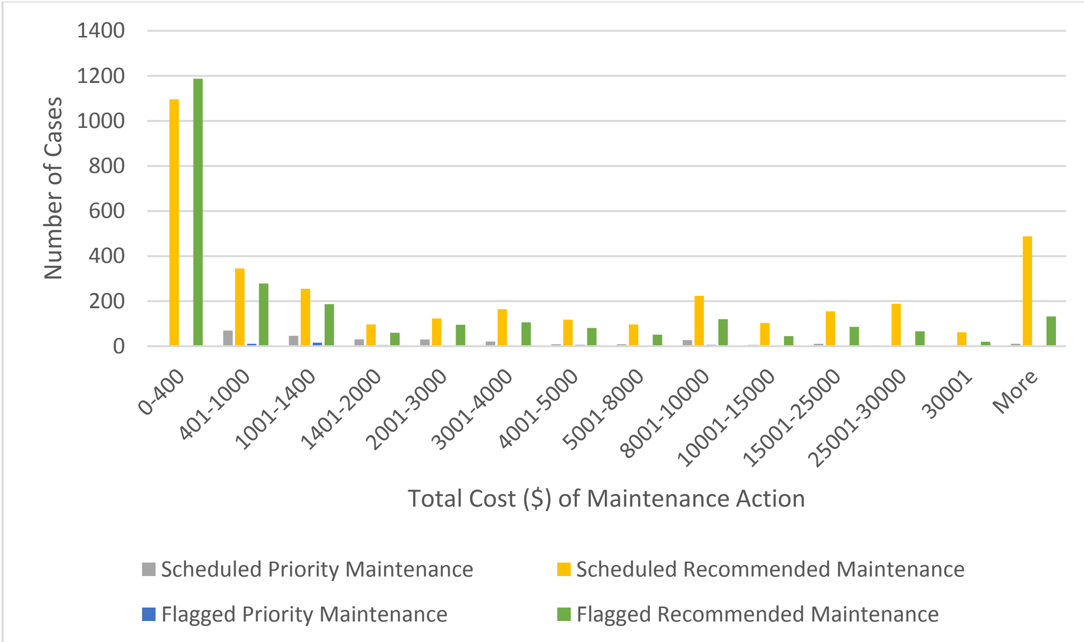


Figure 4.13: Cost of maintenance actions for priority and recommended maintenance of scheduled and non-scheduled for replacement bridges

In conclusion, Figure 4.14 and Figure 4.15 display the cumulative distribution of the total cost of priority and recommended maintenance needs for previously prioritized bridges (bridges both scheduled for replacement and flagged for replacement but not scheduled). As shown in these figures, bridges scheduled for replacement have significantly higher costs for total maintenance needs for both priority and recommended maintenance needs actions. However, for priority maintenance needs, the cost difference is only slightly more (5%) which could relate to the urgency of the needs. The average cost per bridge for priority and recommended maintenance needs is shown in Figures 4.16 and 4.17. In these figures, it is again demonstrated that bridges scheduled for replacement have a greater cost for maintenance needs than that of bridges flagged for replacement but not scheduled.

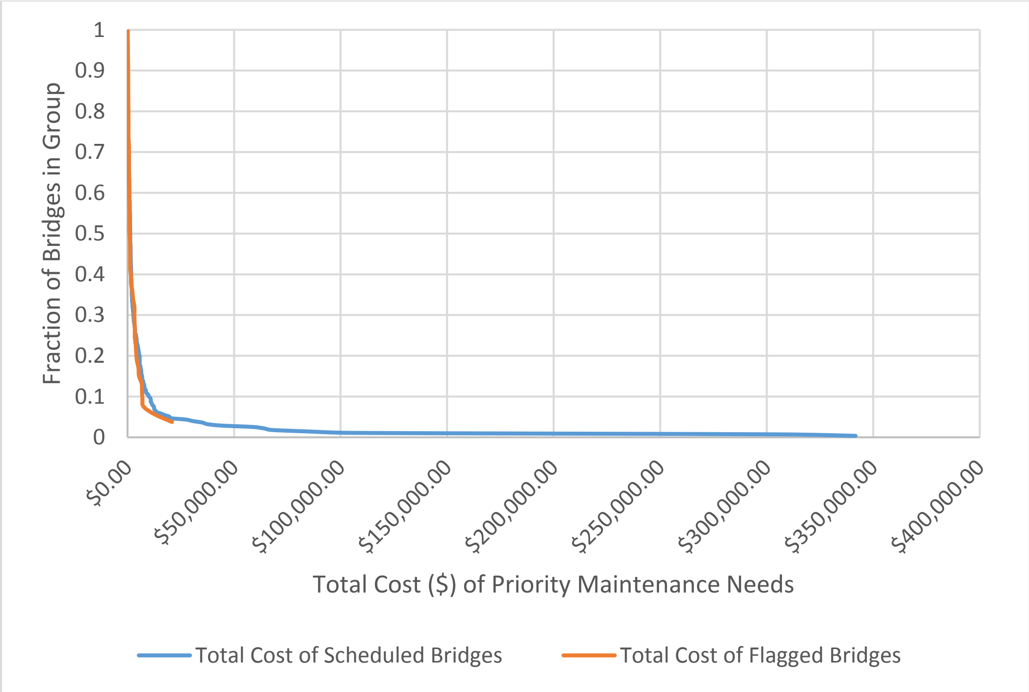


Figure 4.14: Cumulative distribution of maintenance needs cost for scheduled and flagged bridges for priority needs

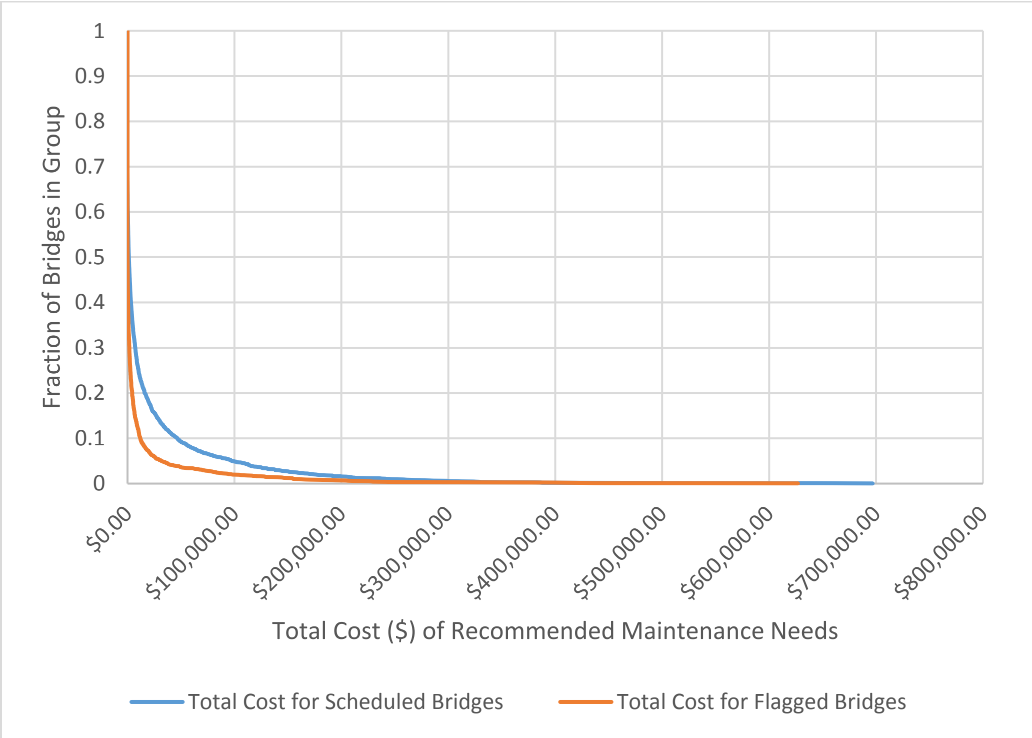


Figure 4.15: Cumulative distribution of maintenance needs cost for scheduled and flagged bridges for recommended data

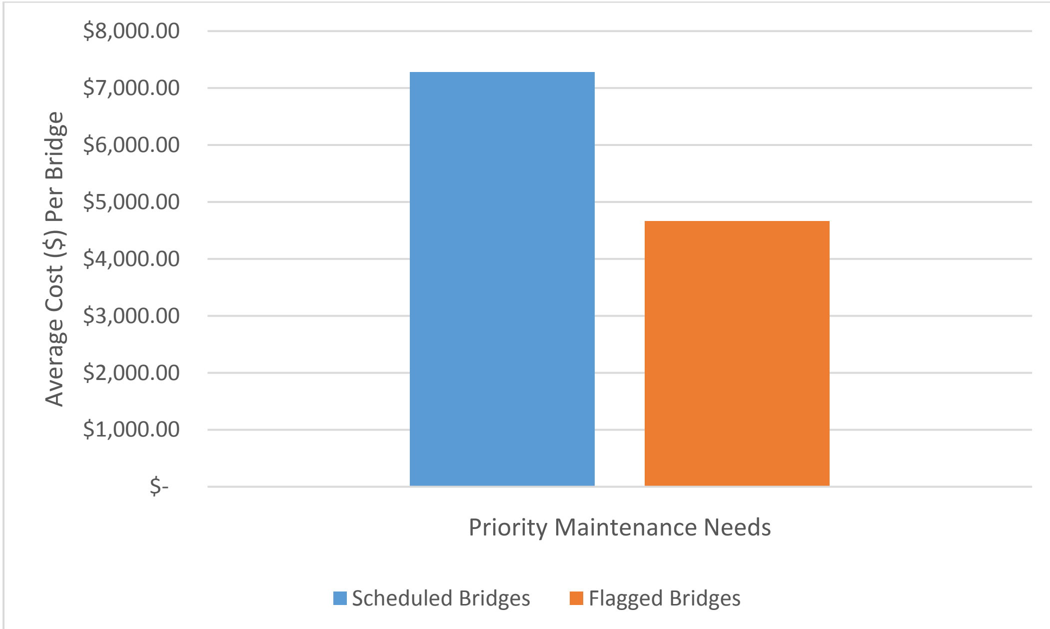


Figure 4.16: Average priority maintenance needs cost per bridge for scheduled and flagged for replacement bridges

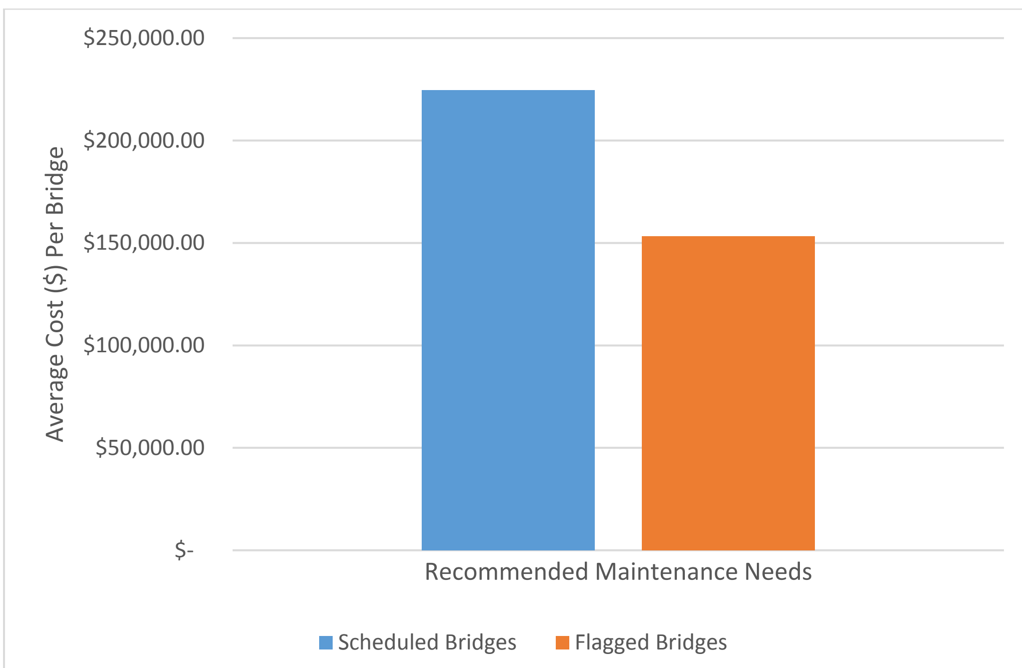


Figure 4.17: Average recommended maintenance needs cost per bridge for scheduled and flagged for replacement bridges

4.3 Summary of Findings and Recommendations

An analysis of maintenance actions performed over the past 10 years for two subsets of bridges (bridges scheduled for replacement and bridges flagged for replacement but not scheduled) revealed that prevalence of maintenance activities (and in particular, reoccurring maintenance activities) could be linked to the previous presence of bridges on both of these prioritization lists. Overall, of the bridges scheduled for maintenance in the BMIP, 494 bridges or 72% have a recorded maintenance action and 208 of those bridges have a case of reoccurring maintenance. For bridges that have been flagged, but are not scheduled for replacement, 377 bridges (or 54%) have recorded maintenance actions and of those 94 one or more instances of reoccurring maintenance actions performed.

Inspector recommended maintenance needs sourced from the BMS could also be readily linked to bridges scheduled for replacement or flagged for replacement but not scheduled. Of the 683 bridges scheduled for replacement, 679 or 99% had recommended maintenance needs, and 230 or 34% had priority maintenance needs. Similarly, of 770 flagged bridges, 739 or 95% had recommended maintenance needs and 191 or 25% had priority maintenance needs. Although there are similarities in the types of recommended and priority maintenance needs associated with bridges scheduled for replacement, and bridges flagged for replacement but not scheduled, the associated costs for these maintenance needs was found to be significantly different for the two subsets of bridges. Costs for priority maintenance needs for bridges scheduled for replacement were significantly higher than costs of these maintenance needs for bridges flagged for replacement but not scheduled.

Based on the results of this analysis, it is evident that both maintenance burden and maintenance needs are significantly linked to bridges previously prioritized by NCDOT. Maintenance burden and maintenance needs are therefore performance criteria that should be used in the new prioritization index for bridge replacement. Additionally, weighting of criteria and measures associated with maintenance burden and maintenance needs could help identify alternatives on the project-scale. For example, if a current bridge has maintenance needs but no prior maintenance history, it may be more suitable for repair than replacement. However, if a bridge has both maintenance needs and prior maintenance history that includes reoccurring maintenance actions, it may be more suitable for replacement.

Based on the analysis performed, recommended performance measures for maintenance burden are:

1) Total amount spent on reoccurring maintenance actions over the past 10 years
2) Total amount spent on reoccurring structural repair maintenance actions over the past 10 years

Recommended performance measures for maintenance needs are:

1) Total cost of priority maintenance needs
2) Total cost of recommended maintenance needs

CHAPTER 5: DEVELOPMENT OF NEW PRIORITIZATION INDICES

5.1. Identification of Performance Criteria and Measures

The MAP-21 legislation states that performance-based measures be utilized in allocation of funding for transportation projects and to aid project prioritization and selection at the system level. In the MAP-21 legislation, seven national performance criteria are identified: safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and project delivery. In this work, a nationwide scan was performed to identify measures and methods utilized by other states for measuring bridge performance and for prioritization of projects. Through this analysis, in conjunction with review of the NCDOT STI, NCDOT P4.0 and the NCHRP Report 590, a set of performance criteria and performance measures were preliminarily developed to be used for NCDOT bridge prioritization, shown in Table 5.1

Table 5.1: Preliminary suggested performance criteria and performance measures, reviewed by NCDOT

Performance Criteria	Performance Measures
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

The list of proposed performance criteria and measures were initially provided to NCDOT for review in the form of a survey (to be discussed in more detail in Chapter 6). Initial survey responses from the NCDOT concluded that several of the proposed criteria and measures, although addressing some federal and statewide goals, were not desirable for inclusion in the new prioritization index. Additionally, NCDOT personnel expressed interest in including bridge maintenance criteria and measures. Based upon a limited number (three) survey responses received, the following summary of direct weighting results on the initially proposed performance criteria and measures was developed, shown in Figure 5.1.

Table 5.2: Initial direct weighting responses from the NCDOT

Performance Criteria and Measures	Weighting
Infrastructure Condition	**44.0**
Deck Condition	9.67
Superstructure Condition Rating	15.33
Substructure Condition Rating	17.33
Element Health Index	1.67
Benefit-Cost	**4.00**
Benefit-Cost	4.00
Safety	**3.33**
Crash Density	1.33
Crash Severity	1.33
Critical Crash Rate	0.67
Congestion Reduction	**4.67**
Exiting Volume	2.67
Existing Volume / Capacity	2.00
Vulnerability	**17.67**
Scour Vulnerability	4.00
Fracture Critical Vulnerability	7.33
Overload Vulnerability	6.33
Economic Vitality	**5.67**
Detour Length	5.67
Freight Mobility	**7.67**
Truck Volume (ADTT)	4.67
Truck Volume / Capacity	2.33
Distance to Freight Terminal	0.67
Multimodal	**1.33**
Volume / Capacity, if near terminal	0.67
Proximity to multimodal terminal	0.67
Functionality	**11.67**
Clear Deck Width Priority	7.67
Vehicle Clearance Priority	4.00

As shown in the above table only five of the nine proposed criteria were given significant weighting. Therefore, in response to this feedback, the following criteria were removed:

- Benefit-Cost
- Safety
- Congestion Reduction

- Multimodal

This initial feedback encouraged the additional work to analyze maintenance burden and maintenance needs data (presented in Chapter 4), as well as other modifications to the proposed performance criteria and measures. The new proposed list of performance criteria and measures, which should be a more accurate reflection of the preferences of the NCDOT and is consistent with the recommendations of NCHRP 590 and current legislation, will be discussed in the subsequent sections.

5.1.2 Performance Measures Retained from PRI

Some performance measures from the current PRI are recommended to be retained in the revised prioritization formula. The following performance measures under the performance criteria of Structural and Functionality are recommended to be retained:

- Deck Condition Rating
- Superstructure Condition Rating
- Substructure Condition Rating

Also, other measures under the performance criteria of deficiency points are recommended to be retained:

- Clear Deck Width Priority
- Vehicle Clearance Priority
- Detour Length

Although these measures are recommended to remain included in the new prioritization index, it is recognized that the relative weighting in the revised formula will likely differ from the current weighting in the current PRI.

5.1.2 Maintenance-Related Performance Measures

In response to the NCDOT's request, the analysis on maintenance burden and maintenance needs was performed, as detailed in Chapter 4. Based on the findings of this analysis, as well as input from NCDOT regarding the preferences of division personnel, the following performance criteria and measures are recommended for inclusion in the new prioritization index:

- Maintenance Needs:
  - Cost of Priority Maintenance Needs
  - Cost of Recommended Maintenance Needs
- Maintenance Burden:
  - Total Cost of Maintenance Performed
  - Total Cost of Reoccurring Maintenance Performed

5.1.3 Other Considerations

In addition to performance criteria and measures recommended to be retained from the current PRI and the new suggested measures associated with maintenance needs and maintenance burden, several additional considerations warrant the identification of some additional performance criteria and measures. Consistent with the considerations included in the STI, as well as input from NCDOT, the following criteria and measures are also suggested for inclusion in the new prioritization index:

- Vulnerability
  - Scour Vulnerability
  - Fracture Critical Vulnerability
  - Overload Vulnerability

- Freight Mobility
    - Truck Volume (ADTT)
    - Truck Volume / Capacity
    - Distance to Freight Terminal

The recommendation of Vulnerability as a performance criteria is consistent with the suggestion of NCHRP 590 to include “protection from extreme events,” with suggested performance measures of scour vulnerability, fatigue/fracture critical, earthquake, collision, overload, and other human-made hazards (Patidar et al., 2007). The recommendation of Freight Mobility is made based upon the current recommendations set by the STI for Prioritization 4.0.

5.2 Summary

The performance criteria and performance measures shown in Table 5.3 are suggested for use in NCDOT’s new prioritization index for bridge replacement projects. This suggested list includes criteria and measures that reflect national goals, recommendations, and current state legislation.

Table 5.3: Recommended performance criteria and performance measures

Performance Criteria	Performance Measures
Infrastructure Condition	Deck Condition Rating
	Superstructure Condition Rating
	Substructure Condition Rating
Vulnerability	Scour Vulnerability
	Fracture Critical Vulnerability
	Overload Vulnerability
Freight Mobility	Truck Volume (ADTT)
	Truck Volume / Capacity
	Distance to Freight Terminal
Functionality	Clear Deck Width Priority
	Vehicle Clearance Priority
Economic Vitality	Detour Length
Maintenance Needs	Cost of Priority Maintenance Needs
	Cost of Recommended Maintenance Needs
Maintenance Burden	Total Cost of Maintenance Performed
	Total Cost of Reoccurring Maintenance Performed

CHAPTER 6: DEVELOPMENT OF SURVEYS FOR RELATIVE WEIGHTING OF RISK AND PREFERENCE

As noted in Chapter 5, the proposed performance criteria and performance measures have been organized and incorporated into a survey to be distributed to NCDOT personnel to facilitate relative weighting for risk and preference. The survey developed as part of this work consists of several sections which facilitate relative weighting through two main survey techniques (as introduced in Chapter 2): direct weighting and the analytical hierarchy process (AHP). For ease of use, the survey has been developed using an Excel spreadsheet that directs respondents through a set of tabs, with each tab structured to include a set of survey components. Each respondent will receive both the survey and an initial instruction sheet that defines the selected performance criteria and measures. Snapshots of the full survey are shown in Appendix B (Figure B.2).

6.1 Direct Weighting

The first section of the survey focuses on establishing relative weighting of performance criteria and measures through direct weighting (introduced in Section 2.2.3.1 Direct Weighting of Chapter 2). Each individual performance criteria and measures is presented in a table (shown in Table 6.1), with a space next to each measure for the respondent to insert his or her preferred weighting. A total of 100 points are available to be allocated between the different measures based on the respondent's preference for significance in bridge prioritization. The yellow box highlights an unanswered response. As the respondent assign points to given measures, the yellow box turns white, and a computed value ("percent left") below the weighting table shows the respondent how many points are still available to be allocated amongst the criteria and measures. Once all 100 points are assigned, the "total" box turns red to indicate the respondent has reached the maximum amount of allocable points.

Table 6.1: Direct weighting survey

Performance Criteria	Performance Measures	Weight
Infrastructure Condition	Deck Condition Rating	10
	Superstructure Condition Rating	10
	Substructure Condition Rating	10
Vulnerability	Scour Vulnerability	
	Fracture Critical Vulnerability	
	Overload Vulnerability	
Economic Vitality	Detour Length	4
Freight Mobility	Truck Volume (ADTT)	4
	Truck Volume / Capacity	4
	Distance to Freight Terminal	4
Functionality	Clear Deck Width Priority	6
	Vehicle Clearance Priority	6
Maintenance Needs	Cost of Priority Maintenance Needs	
	Cost of Recommended Maintenance Needs	
Maintenance Burden	Total Cost of Maintenance Performed	
	Total Cost of Reoccurring Maintenance	

Percent Left	42
Total	58

6.2 Analytical Hierarchy Process (AHP)

On the second tab of the survey, sets of pairwise comparisons for the analytical hierarchy process (AHP) (discussed in Section 2.2.3.3 Analytical Hierarchy Process (AHP) of Chapter 2) are presented. Again, using the proposed performance criteria and measures, the respondents are asked to define their preference between each performance criteria and measure, and assign a number associated with the relative degree of importance for the preferred criteria or measures. The questions were arranged in the survey in a manner similar to that utilized by Johnson and Ozbek (2013), explained in Section 2.4.3.3.2 Survey Process.

This portion of the survey is comprised of two sections. The first section facilitates relative weighting of the recommended performance criteria. The second portion of the survey facilitates relative weighting of the performance measures. A snapshot of each section is shown in Table 6.2 and Table 6.3. Snapshots of the full survey is provided in the Appendix B (Figure B.1).

Table 6.2: Snapshot of AHP Part 1: performance criteria questionnaire

Part 1: Performance Criteria

Item A	Item B	More Important	Degree of Importance
Infrastructure Condition	Maintenance Needs		
Infrastructure Condition	Maintenance Burden		
Infrastructure Condition	Vulnerability		
Infrastructure Condition	Economic Vitality		
Infrastructure Condition	Freight Mobility		
Infrastructure Condition	Functionality		
		More Important Goal	Degree of Importance
Maintenance Needs	Maintenance Burden		
Maintenance Needs	Vulnerability		
Maintenance Needs	Economic Vitality		
Maintenance Needs	Freight Mobility		
Maintenance Needs	Functionality		
Maintenance Needs	Infrastructure Condition		
		More Important Goal	Degree of Importance
Maintenance Burden	Maintenance Needs		
Maintenance Burden	Vulnerability		
Maintenance Burden	Economic Vitality		
Maintenance Burden	Freight Mobility		
Maintenance Burden	Functionality		
Maintenance Burden	Infrastructure Condition		
		More Important Goal	Degree of Importance
Vulnerability	Infrastructure Condition		
Vulnerability	Maintenance Needs		
Vulnerability	Maintenance Burden		
Vulnerability	Economic Vitality		
Vulnerability	Freight Mobility		
Vulnerability	Functionality		

Table 6.3: Snapshot of AHP Part 2: performance measure questionnaire

Part 2: Performance Measures

Item A	Item B	More Important	Degree of Importance
Deck Condition	Superstructure Condition Rating		
Deck Condition	Substructure Condition Rating		
		More Important Measure	Degree of Importance
Superstructure Condition Rating	Deck Condition		
Superstructure Condition Rating	Substructure Condition Rating		
		More Important Measure	Degree of Importance
Substructure Condition Rating	Deck Condition		
Substructure Condition Rating	Superstructure Condition Rating		
		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		

To facilitate ranking of relative importance, each respondent is presented the scale of importance. For this survey, choices consisted of 1, 3, 5, 7, 9 (Table 6.4), with 1 associated with choices being equally important to each other, and 9 associated with one choice being far more important than the other. It is noted that this scale utilizes odd numbers only (as recommended in NCHRP Report 590), which helps to increase consistency. Also, in this survey, instead of presenting the numbers under the drop down box for degree of importance, only the wording is included. For example, instead of 5, “Moderately More Important” appeared. This was done to help avoid any confusion about the direction of the numerical scale (from more to less important).

Table 6.4: Degree of importance ranking

Degree of Importance Ranking	
Intensity of Importance	**Explanation**
1	Goal/Measures are equally important
3	Goal/Measure is slightly more important
5	Goal/Measure is moderately more important
7	Goal/Measure is strongly more important
9	Goal/Measure is extremely more important

The respondent is directed to fill in each blank under “More Important” and “Degree of Importance.” As with the direct weighting portion of the survey, a yellow box is displayed when a response is needed.

An additional tab focused on maintenance burden and maintenance needs criteria and measures is also included in the survey. Given the desire of NCDOT personnel to incorporate maintenance activities and needs into the new prioritization index, this information is being collected in order to determine how respondents weight particular maintenance factors that are driving maintenance cost. It is noted that this section of the survey will not be used to determine weighting for the Priority Replacement Index. The sole purpose is to see if the respondents scale the selected maintenance actions in the same or similar order to what the data showed. In this section of the survey, thee following maintenance actions will be compared:

Maintenance Needs:

- Maintain Timber Superstructure Components
- Repair/replace Timber Substructure Components
- Maintain Steel Superstructure Components
- Maintain Concrete Superstructure Components
- Maintain Concrete Substructure Components
- Maintain Concrete Deck

Maintenance Burden:

- Repair/replace Timber Substructure Components
- Maintain Timber Deck Components
- Maintain Steel Substructure Components
- Maintain Concrete Deck Components

A snapshot of the Maintenance Burden portion of the survey is shown in Table 6.5 and an example of the Maintenance Needs portion of the survey is shown in Table 6.6. Snapshots of the complete version of this portion of the survey are provided in Appendix B. (Figure B.2).

Table 6.5: Snapshot of maintenance burden AHP survey

Maintenance Burden			
Item A	**Item B**	**More Important**	**Degree of Importance**
Repair / Replace Timber Substructure	Maintain Steel Superstructure Components		
Repair / Replace Timber Substructure	Maintain Concrete Deck		
Repair / Replace Timber Substructure	Maintain Timber Deck Components		
		More Important Measure	Degree of Importance
Maintain Steel Superstructure Components	Maintain Concrete Deck		
Maintain Steel Superstructure Components	Maintain Timber Deck Components		
Maintain Steel Superstructure Components	Repair / Replace Timber Substructure		
		More Important Measure	Degree of Importance
Maintain Concrete Deck	Maintain Timber Deck Components		
Maintain Concrete Deck	Repair / Replace Timber Substructure		
Maintain Concrete Deck	Maintain Steel Superstructure Components		
		More Important Measure	Degree of Importance
Maintain Timber Deck Components	Repair / Replace Timber Substructure		
Maintain Timber Deck Components	Maintain Steel Superstructure Components		
Maintain Timber Deck Components	Maintain Concrete Deck		

Table 6.6: Snapshot of maintenance needs AHP survey

Maintenance Needs			
Item A	Item B	More Important	Degree of Importance
Repair / Replace Timber Substructure	Maintain Timber Superstructure Components		
Repair / Replace Timber Substructure	Maintain Steel Superstructure Components		
Repair / Replace Timber Substructure	Maintain Concrete Superstructure Components		
Repair / Replace Timber Substructure	Maintain Concrete Substructure Components		
Repair / Replace Timber Substructure	Maintain Concrete Deck		
		More Important Measure	Degree of Importance
Maintain Timber Superstructure Components	Maintain Steel Superstructure Components		
Maintain Timber Superstructure Components	Maintain Concrete Superstructure Components		
Maintain Timber Superstructure Components	Maintain Concrete Substructure Components		
Maintain Timber Superstructure Components	Maintain Concrete Deck		
Maintain Timber Superstructure Components	Repair / Replace Timber Substructure		
		More Important Measure	Degree of Importance
Maintain Steel Superstructure Components	Maintain Concrete Superstructure Components		
Maintain Steel Superstructure Components	Maintain Concrete Substructure Components		
Maintain Steel Superstructure Components	Maintain Concrete Deck		
Maintain Steel Superstructure Components	Repair / Replace Timber Substructure		
Maintain Steel Superstructure Components	Maintain Timber Superstructure Components		

6.3 Mid-Value Splitting Technique

In the initial survey presented to NCDOT (discussed in Section 5.1.1 of Chapter 5), preferences regarding improvements to condition ratings were assessed using the mid-value splitting technique (as discussed in Section 2.2.2.1 of Chapter 2). This method was selected for this portion of the survey, as recommended in the NCHRP Report 590 (Patidar et al. 2007). The tab in this Excel-based survey included both detailed instruction on how the mid-value splitting process worked as well as an example on how to answer the question set. In Table 6.8, the instructions presented for the mid-value splitting portion of the survey are shown, and in Table 6.9, an example of this portion of the survey in process is shown. After receiving feedback from the NCDOT, this portion of the survey was removed due to confusion of the respondents on how to complete the survey. A full copy of this survey is shown in Appendix B (Figure B.1).

Table 6.8: Mid-value splitting technique survey instructions

Part 1 - 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:								

Table 6.9: Snapshot of Mid-value splitting technique survey

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:	
	[redacted]
Answer:	

Deck Condition Rating - Question 4	
Consistency check: In general, are you equally satisfied with an deck condition 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.

6.4 Delphi Technique

The Delphi Technique process allows respondents to analyze and reflect on the combined survey results. This therefore enables the respondents to determine if their individual response was similar or not to the group's overall result. Also, the group can discuss if the result is adequate or not to address their desired outcome. After this process, each respondent is given the opportunity to retake the survey and either keep their initial answers or adjust them based on newly presented information. This consensus-based survey technique is recommended for consolidation of individual NCDOT personnel survey responses, facilitating identification of the final weighting of performance criteria and measures in a means consistent with stakeholders' attitudes on preference and risk.

6.5 Recommended Approach for Survey Dissemination and Analysis

The survey presented in this chapter should facilitate relative weighting of the recommended performance criteria and measures for use in a new bridge prioritization index. The recommended approach for survey dissemination and analysis includes the following steps:

1. Distribute the survey. It is anticipated that survey respondents will include NCDOT personnel who are members of the Steering and Implementation Committee for NCDOT Research Project 2016-05 as well as division engineers involved in section of bridge replacement projects
2. Analyze the responses from the survey and determine the combined group results

3. Meet with the survey respondents in order to discuss the results, in a manner consistent with the Delphi Technique
4. Redistribute the survey
5. Analyze the results of the second survey and determine the combined group relative weightings

   a. Results of the direct weightings will be combined by averaging each result.

   b. Results of the AHP portion of the survey will be combined using the geometric mean of the results and then developing a final pairwise comparison using the mean, as outlined in Section 2.4.3.3.4 Combing Survey Results, in Chapter 2
6. Compare the results from directing weighting to AHP
   a. Determine which one will be used in the final weighting, designated by the approval of the appropriate NCDOT personnel
7. Confirm the relative weightings of the new prioritization indices with feedback from NCDOT personnel

Due to the fact that both the direct weighting and AHP portion of the survey are using the same performance criteria and performance measures, this allows for cross validation of the results. The respondents again will be able to analyze the results and determine which one best fits their personal preference. This will then result in the confirmed final weightings to be used with the newly developed bridge prioritization process.

6.6 Summary

In order to develop the new prioritization index for NCDOT's prioritization of bridge replacement projects, the performance criteria and measures recommended for use in Chapter 5 will need to be weighted to appropriately reflect the risk and preference of NCDOT personnel. The survey proposed in this chapter utilizes several accepted surveying techniques, and is consistent with the recommendations of NCHRP 590. By using both direct weighting and AHP methods, results can be compared (and potentially combined) to adequately express the NCDOT's risk and preference in the new bridge prioritization index. Use of the Delphi Technique during the survey process should also facilitate consensus building for the NCDOT stakeholders. This survey process, although not yet carried out, has been preliminarily approved by the NCDOT and will be conducted in future research.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Work presented in this thesis supported identification of performance criteria and measures for prioritization of bridge replacement. Specific contributions include the following:

- A literature review and nationwide scan of SHAs to identify performance criteria and measures for prioritization of bridge projects
- Breakdown and assessment of the current PRI utilized by NCDOT to prioritize bridge replacement projects
- Assessment of maintenance burden and maintenance history data for use in the future prioritization index
- Identification of appropriate performance goals (criteria) and measures that move towards current legislative goals while balancing agency preferences and risk tolerances, and
- Development of a surveys for relative weightings for performance criteria and measures

The analysis of the PRI presented in Chapter 3 demonstrated that there are currently many factors influencing the current prioritization index. Some factors are essentially double-counted factors (influencing the PRI through multiple performance criteria such as deficiency points and sufficiency rating), while other characteristics that could be linked to current federal and state goals do not appear in the current PRI. Results of the current PRI analysis concludes that the characteristics that most significantly influence the PRI are largely related to traffic, bridge condition, and indirectly to safety. Through this analysis, measures included in the STI Law to determine the prioritization of transportation project were found to not be highly reflected in the PRI. This supports NCDOT's decision to pursue development of a new bridge project prioritization index, including new performance criteria and measures that more adequately reflect federal and state goals, with weighting more in line with agency preferences and risk tolerance.

Results of the maintenance burden and maintenance needs analysis indicate that these prior maintenance actions and recommended needs are significantly linked to bridges previously prioritized by NCDOT. Maintenance burden and maintenance needs are therefore performance criteria that should be used in the new prioritization index for bridge replacement. Additionally, weighting of criteria and measures associated with maintenance burden and maintenance needs could help identify alternatives on the project-scale. Based on the analysis performed, recommended performance measures for maintenance burden are:

1) Total amount spent on reoccurring maintenance actions over the past 10 years
2) Total amount spent on reoccurring structural repair maintenance actions over the past 10 years

Recommended performance measures for maintenance needs are:

1) Total cost of priority maintenance needs
2) Total cost of recommended maintenance needs

New performance criteria and measures for NCDOT's new bridge repair, rehabilitation, and replacement index (in development), are presented in Chapter 5, shown in Table 5.3. To appropriately reflect the risk and preference of NCDOT personnel, relative weighting of these criteria and measures will need to be established using survey methods. The survey proposed in Chapter 6 utilizes several established survey techniques and is consistent with the recommendations of NCHRP Report 590. By using both direct weighting and AHP, the results from the surveys serve for cross validation to ensure that the developed bridge prioritization index adequately expresses NCDOT risk and preference structure. Use of the Delphi Technique during the survey process should also facilitate consensus building for the NCDOT stakeholders. This survey process, although not yet carried out, has been preliminarily approved by the NCDOT and will be conducted in future research.

7.2 Recommendations for Future Work

To facilitate relative weighting of the recommended performance criteria and measures for use in a new bridge prioritization index, the survey discussed in Chapter 6 should be distributed and the results analyzed. It is anticipated that survey respondents will include NCDOT personnel who are members of the Steering and Implementation Committee for NCDOT Research Project 2016-05. The survey responses should be analyzed, and the combined group results should be discussed in a manner consistent with the Delphi Technique. After redistribution of the survey, the results should be combined to establish the group relative weightings. Direct weighting results could be compared to results indicated through AHP. Ultimately, the final relative weightings could be reviewed and confirmed by NCDOT personnel. This work can ultimately be combined with the results of concurrent efforts to develop value functions to establish the new bridge project prioritization index for NCDOT.

Results could then be validated by comparing predictions to future projects actually selected by NCDOT. Additional analysis should also be performed to ensure that the index creates the desired “spread” across the numerical scale, so that the index clearly identifies optimal projects rather than clustering candidates.

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APPENDIX A: SUPPLEMENTARY TABLES AND FIGURES

Table A.1: Reoccurring maintenance summary for bridges scheduled for replacement and flagged, but not scheduled.

Reocurring Maintenance Data for Bridges Scheduled for Replacement and Flagged, but not Scheduled for Replacement																
Reoccurring Maintenance Factors for Bridges on Replacment list:	Number of Bridges with 2 or more cases of reoccurring (# of bridges)	Total Number of Reoccurring Cases	Unit of Measure	Average Number of reoccurring cases per bridge	Total Number of Cases (Both reoccurring and non-reoccurring)	Percentage of Cases Reoccurring	Total Number of Bridges with the maintenance type	Percent of Bridges with reoccuring maintenance	Total Cost of Reoccurring Maintenance	Average Cost of Reoccuring Maintenance	Average Cost of Non-reoccruing Manitenance	Total Quantity	Total Cost of all Maintenance	Percent of reoccurring bridges to to Total # of bridges	Percent of Bridges with Maintenance Action Performed
Asphalt Pavement Repair and Patching	2	6	$/Sq. Ft	3.00	26	23%	22	9%	$ 22,927.99	$ 3,821.33	$ 2,463.08	793.93	$ 72,189.62	0.22%	2%
Maintain Timber Superstructure Components	10	23	$/LF	2.30	70	33%	57	18%	$ 376,241.98	$ 16,358.35	$ 11,203.05	8626.00	$ 902,785.39	1.12%	6%
Maintain Concrete Superstructure Components	13	27	$/Sq. Ft	2.08	78	35%	64	20%	$ 411,009.65	$ 15,222.58	$ 9,430.74	4933.20	$ 891,977.52	1.45%	7%
Maintain/Repair Bridge Exp. Joint	13	27	$/LF	2.08	81	33%	67	19%	$ 131,946.56	$ 4,886.91	$ 2,802.36	6657.10	$ 283,274.08	1.45%	7%
Maintain Steel Superstructure Components	30	68	$/Sq. Ft	2.27	193	35%	155	19%	$ 2,125,939.00	$ 31,263.81	$ 12,908.86	16687.21	$ 3,739,546.51	3.35%	17%
Maintain Timber Deck Components	22	64	$/Sq. Ft	2.91	137	47%	95	23%	$ 583,641.60	$ 9,119.40	$ 17,725.39	53131.56	$ 1,877,594.79	2.46%	11%
Maintain Concrete Deck	16	56	$/Sq. Ft	3.50	108	52%	68	24%	$ 782,618.40	$ 13,975.33	$ 8,834.34	52767.95	$ 1,242,003.85	1.79%	8%
Maintain/Repair/Replace Steel Plank Bridge Floor	4	13	$/Sq. Ft	3.25	24	54%	15	27%	$ 96,484.94	$ 7,421.92	$ 10,059.65	3488.18	$ 207,141.07	0.45%	2%
Maintain Movable Bridges	1	12	Each	12.00	16	75%	5	20%	$ 551,106.59	$ 45,925.55	$ 2,461.71	13838	$ 560,953.44	0.11%	1%
Operations of Movable Bridges	1	6	Each	6.00	6	100%	1	100%	$ 1,412,547.93	$ 235,424.66	$ -	1412547.93	$ 1,412,547.93	0.11%	0%
Repair/Replace Timber Substructure Components	42	95	$/LF	2.26	292	33%	239	18%	$ 1,531,766.83	$ 16,123.86	$ 11,628.69	16764.94	$ 3,822,618.02	4.69%	27%
Repair/Maintain Timber Wings and Blkhds.	20	42	$/Sq. Ft	2.10	150	28%	128	16%	$ 599,031.03	$ 14,262.64	$ 7,505.34	18686.08	$ 1,409,608.20	2.23%	14%
Maintain Concrete Substructure Components	8	16	$/LF	2.00	76	21%	68	12%	$ 240,029.41	$ 15,001.84	$ 18,046.32	3360.666667	$ 1,322,808.43	0.89%	8%
Maintain Slope Protection	2	4		2.00	63	6%	61	3%	$ 198,591.32	$ 49,647.83	$ 4,358.90	10849.83333	$ 455,766.40	0.22%	7%
Maintain / Repair Steel Substructure Components	4	10	$/LF	2.50	30	33%	24	17%	$ 161,144.93	$ 16,114.49	$ 38,768.58	2579.2	$ 936,516.44	0.45%	3%
Maintenance and Repair of Fender System	1	3	$/LF	3.00	4	75%	2	50%	$ 139,327.47	$ 46,442.49	$ 337.50	480.7222222	$ 139,664.97	0.11%	0%
Maintain Concrete Bridge Floor	1	2	$/Sq. Ft	2.00	16	13%	15	7%	$ 10,600.96	$ 5,300.48	$ 5,377.19	2177.85	$ 85,881.58	0.11%	2%
Repair Steel Plank Bridge Floor	1	2	$/Sq. Ft	2.00	4	50%	3	33%	$ 2,756.27	$ 1,378.14	$ 4,007.07	426.06	$ 10,770.40	0.11%	0%
Maintain Deck Expansion Joints	2	4	$/LF	2.00	20	20%	18	11%	$ 13,236.73	$ 3,309.18	$ 1,712.13	852.8	$ 40,630.82	0.22%	2%
Maintain Timber Piles and Posts	1	2		2.00	14	14%	13	8%	$ 38,979.71	$ 19,489.86	$ 7,304.59	245	$ 126,634.82	0.11%	1%
Bridge Installation and Repair	2	4		2.00	10	40%	8	25%	$ 151,439.70	$ 37,859.93	$ 63,701.74	5794.44	$ 533,650.15	0.22%	1%
Maintain Steel Plate Bridge Joint	1	2		2.00	3	67%	2	50%	$ 5,342.38	$ 2,671.19	$ 7,725.68	145	$ 13,068.06	0.11%	0%

Table A.2: Reoccurring maintenance summary for bridges scheduled for replacement

Reoccurring Maintenance Data for Bridges Scheduled for Replacement Bridges:															
Reoccurring Maintenance Factors for Bridges:	Number of Bridges with 2 or more cases of reoccurring (# of bridges)	Total Number of Reoccurring Cases	Unit of Measure	Average Number of reoccurring cases per bridge	Total Number of Cases (Both reoccurring and non-reoccurring)	Percentage of Cases Reoccurring	Total Number of Bridges with the maintenance type	Percent of Bridges with reoccuring maintenance	Total Cost of Reoccurring Maintenance	Average Cost of Reoccuring Maintenance	Average Cost of Non-reoccruing Manitenance	Total Quantity	Total Cost of all Maintenance	Percent of reoccurring bridges to to Total # of bridges	Percent of Bridges with Maintenance Action Performed
Asphalt Pavement Repair and Patching	2	6	$/Sq. Ft	3.00	15	40%	11	18%	$ 16,887.61	$ 2,814.60	$ 2,916.20	222.44	$ 43,133.38	0.40%	2%
Maintain Timber Superstructure Components	9	20	$/LF	2.22	43	47%	32	28%	$ 337,800.16	$ 16,890.01	$ 12,915.95	6731.00	$ 634,866.90	1.80%	6%
Maintain Concrete Superstructure Components	11	23	$/Sq. Ft	2.09	70	33%	58	19%	$ 394,863.77	$ 17,167.99	$ 9,802.00	4676.20	$ 855,557.79	2.20%	12%
Maintain/Repair Bridge Exp. Joint	12	25	$/LF	2.08	70	36%	57	21%	$ 87,840.13	$ 3,513.61	$ 3,323.24	6230.52	$ 237,386.13	2.40%	11%
Maintain Steel Superstructure Components	20	48	$/Sq. Ft	2.40	118	41%	90	22%	$ 1,834,345.33	$ 38,215.53	$ 18,299.97	11828.28	$ 3,115,342.98	4.01%	18%
Maintain Timber Deck Components	11	30	$/Sq. Ft	2.73	59	51%	40	28%	$ 391,190.36	$ 13,039.68	$ 22,080.83	30758.33	$ 1,031,534.45	2.20%	8%
Maintain Concrete Deck	14	51	$/Sq. Ft	3.64	97	53%	60	23%	$ 771,927.63	$ 15,135.84	$ 8,234.86	47943.31	$ 1,150,731.07	2.81%	12%
Maintain/Repair/Replace Steel Plank Bridge Floor	2	6	$/Sq. Ft	3.00	13	46%	9	22%	$ 78,243.31	$ 13,040.55	$ 7,938.87	842.18	$ 133,815.38	0.40%	2%
Maintain Movable Bridges	1	12	Each	12.00	14	86%	3	33%	$ 550,669.58	$ 45,889.13	$ 4,722.44	13820	$ 560,114.45	0.20%	1%
Operations of Movable Bridges	1	6	Each	6.00	6	100%	1	100%	$ 1,412,547.93	$ 235,424.66	$ -	1412547.93	$ 1,412,547.93	0.20%	0%
Repair/Replace Timber Substructure Components	31	70	$/LF	2.26	163	43%	124	25%	$ 1,209,848.83	$ 17,283.55	$ 16,011.91	10588.6	$ 2,698,956.84	6.21%	25%
Repair/Maintain Timber Wings and Blkhds.	10	21	$/Sq. Ft	2.10	77	27%	66	15%	$ 546,987.72	$ 26,047.03	$ 9,422.60	12361.49	$ 1,074,653.19	2.00%	13%
Maintain Concrete Substructure Components	8	16	$/LF	2.00	63	25%	55	15%	$ 240,029.41	$ 15,001.84	$ 17,098.85	1745.666667	$ 1,043,675.31	1.60%	11%
Maintain Slope Protection	2	4		2.00	38	11%	36	6%	$ 195,219.52	$ 48,804.88	$ 5,599.42	6035.5	$ 385,599.76	0.40%	7%
Maintain / Repair Steel Substructure Components	4	10	$/LF	2.50	23	43%	17	24%	$ 152,024.84	$ 15,202.48	$ 47,229.56	2222.2	$ 766,009.17	0.80%	3%
Maintenance and Repair of Fender System	1	3	$/LF	3.00	4	75%	2	50%	$ 139,327.47	$ 46,442.49	$ 337.50	480.7222222	$ 139,664.97	0.20%	0%
Maintain Concrete Bridge Floor	1	2	$/Sq. Ft	2.00	14	14%	13	8%	$ 10,600.96	$ 5,300.48	$ 5,740.89	2153.85	$ 79,491.60	0.20%	3%
Maintain Deck Expansion Joints	2	4	$/LF	2.00	18	22%	16	13%	$ 13,236.73	$ 3,309.18	$ 1,728.79	830.8	$ 37,439.80	0.40%	3%
Maintain Timber Piles and Posts	1	2		2.00	10	20%	9	11%	$ 38,979.71	$ 19,489.86	$ 10,168.42	209	$ 120,327.09	0.20%	2%
Bridge Installation and Repair	1	2		2.00	3	67%	2	50%	$ 106,566.17	$ 53,283.09	$ 61,333.00		$ 167,899.17	0.11%	0%
Maintain Steel Plate Bridge Joint	1	2		2.00	3	67%	2	50%	$ 5,342.38	$ 2,671.19	$ 7,725.68	145	$ 13,068.06	0.11%	0%

Table A.3: Reoccurring maintenance summary for bridges flagged but not scheduled for replacement

Reoccurring Maintenance Data for Bridges Flagged but Non-Scheduled Bridges:															
Reoccurring Maintenance Factors for Bridges:	Number of Bridges with 2 or more cases of reoccurring (# of bridges)	Total Number of Reoccurring Cases	Unit of Measure	Average Number of reoccurring cases per bridge	Total Number of Cases (Both reoccurring and non-reoccurring)	Percentage of Cases Reoccurring	Total Number of Bridges with the maintenance type	Percent of Bridges with reoccuring maintenance	Total Cost of Reoccurring Maintenance	Average Cost of Reoccuring Maintenance	Average Cost of Non-reoccruing Manitenance	Total Quantity	Total Cost of all Maintenance	Percent of reoccurring bridges to to Total # of bridges	Percent of Bridges with Maintenance Action Performed
Asphalt Pavement Repair and Patching	0	0	$/Sq. Ft	0.00	0	0%	0	0%	$ -	$ -	$ -	0.00	$ -	0.00%	0%
Maintain Timber Superstructure Components	1	3	$/LF	3.00	27	11%	25	4%	$ 38,441.82	$ 12,813.94	$ 9,561.53	1895.00	$ 267,918.49	0.25%	6%
Maintain Concrete Superstructure Components	2	4	$/Sq. Ft	2.00	8	50%	6	33%	$ 16,145.88	$ 4,036.47	$ 5,068.46	257.00	$ 36,419.73	0.50%	2%
Maintain/Repair Bridge Exp. Joint	1	2	$/LF	2.00	8	25%	7	14%	$ 44,106.43	$ 22,048.76	$ 298.41	426.59	$ 45,887.95	0.25%	2%
Maintain Steel Superstructure Components	10	20	$/Sq. Ft	2.00	75	27%	65	15%	$ 291,593.67	$ 14,570.08	$ 6,050.94	4858.93	$ 624,203.52	2.52%	16%
Maintain Timber Deck Components	11	30	$/Sq. Ft	2.73	78	38%	59	19%	$ 192,451.24	$ 5,383.80	$ 14,261.39	22373.23	$ 846,060.34	2.77%	15%
Maintain Concrete Deck	2	5	$/Sq. Ft	2.50	11	45%	8	25%	$ 10,690.77	$ 1,062.88	$ 14,326.39	4824.64	$ 91,272.78	0.50%	2%
Maintain/Repair/Replace Steel Plank Bridge Floor	2	7	$/Sq. Ft	3.50	11	64%	6	33%	$ 18,241.63	$ 2,605.95	$ 13,771.02	2646.00	$ 73,325.69	0.50%	2%
Maintain Movable Bridges	0	0	Each	0.00	0	0%	0	0%	$ -	$ -	$ -	0	$ -	0.00%	0%
Operations of Movable Bridges	0	0	Each	0.00	0	0%	0	0%	$ -	$ -	$ -	0	$ -	0.00%	0%
Repair/Replace Timber Substructure Components	11	25	$/LF	2.27	129	19%	115	10%	$ 321,918.00	$ 12,039.09	$ 7,910.42	6176.34	$ 1,123,661.18	2.77%	29%
Repair/Maintain Timber Wings and Blkhds.	10	21	$/Sq. Ft	2.10	77	27%	66	15%	$ 546,987.72	$ 26,047.03	$ 9,422.60	12361.49	$ 1,074,653.19	2.00%	17%
Maintain Concrete Substructure Components	0	0	$/LF	0.00	0	0%	0	0%	$ -	$ -	$ -	0	$ -	0.00%	0%
Maintain Slope Protection	0	0		0.00	0	0%	0	0%	$ -	$ -	$ -	0	$ -	0.00%	0%
Maintain / Repair Steel Substructure Components	0	0	$/LF	0.00	0	0%	0	0%	$ -	$ -	$ -	0	$ -	0.00%	0%
Maintenance and Repair of Fender System	0	0	$/LF	0.00	0	100%	0	100%	$ -	$ -	$ -	0	$ -	0.00%	0%
Maintain Concrete Bridge Floor	0	0	$/Sq. Ft	0.00	0	200%	0	200%	$ -	$ -	$ -	0	$ -	0.00%	0%
Maintain Deck Expansion Joints	0	0	$/LF	0.00	0	300%	0	300%	$ -	$ -	$ -	0	$ -	0.00%	0%
Maintain Timber Piles and Posts	0	0		0.00	0	400%	0	400%	$ -	$ -	$ -	0	$ -	0.00%	0%
Bridge Installation and Repair	1	2		2.00	7	29%	6	17%	$ 44,873.53	$ 22,436.77	$ 64,175.49	5794.44	$ 365,750.98	0.11%	1%
Maintain Steel Plate Bridge Joint	0	2		0.00	0	0%	0	0%	$ -	$ -	$ -	0	$ -	0.00%	0%

Table A.4: Cost data of priority maintenance for bridges flagged, but not scheduled for replacement

	Priority Maintenance					
Maintenance Number	**Maintenance Type**	**Number of Cases**	**Quantities**	**Average Cost**	**Total Area or LF**	**Total Cost By Quantity**
3304	Maintain/Replace Timber Superstructure Components	24	967	$111.58	722	$107,897.86
3306	Maintain Concrete Superstructure Components	7	550	$132.19	49022.614	$72,704.50
3308	Maint. Of Steel Plate Bridge Joints	-	0	$114.80	0	$0.00
3310	Maintenance/Repair/Replacement of Standard Bridge Expansion Joints	-	0	$ 23.60	0	$0.00
3312	Maint/Replace/Repair Modular Bridge Joints	-	0	$125.56	0	$0.00
3314	Maintain Steel Superstructure Components	65	3103	$196.60	107960.895	$610,049.80
3316	Maint to Timber Handrail	16	371	$ 12.41	1002	$4,604.11
3318	Maint to Concrete Handrail	2	121	$192.05	90	$23,238.05
3320	Maint to Aluminum Handrail	-	0	$ 84.58	0	$0.00
3322	Maint to Steel Handrail	1	15	$ 39.90	23	$598.50
3324	Maint / Repair / Replace Timber Deck Components	17	2048	$ 36.29	12283.2	$74,321.92
3326	Maintain Concrete Deck	2	120	$ 25.20	33751.418	$3,024.00
3328	Maintenance/Repair/ Replace Steel Plank Bridge Floor	-	0	$ 56.64	0	$0.00
3330	Maintenance/Repair Open Grid Steel Floor	-	0	$102.94	0	$0.00
3332	Maint Drainage System - Bridge	-	0	$ 2.42	0	$0.00
3334	Bridge Bearings	1	1	$218.46	1	$218.46
3336	Moveable Bridges (Maintenance)	-	0	$ 40.20	0	$0.00
3342	Clean and Paint Structural Steel	-	0	$ 7.18	0	$0.00
3344	Repair / Replace Timber Substructure Components	75	982	$214.70	3374	$210,835.40
3346	Repair / Maintain Timber Wings & Blkhds	36	2259	$ 41.31	25901.343	$93,319.29
3348	Maintain Concrete Substructure Components	5	146	$209.91	994	$30,646.86
3350	Maint R C Wings and Walls	-	0	$121.50	0	$0.00
3352	Maint Slope Protection	12	554	$ 14.89	11419.876	$8,249.06
3354	Maintain Steel Substructure Components	-	0	$273.54	0	$0.00
3362	Maintenance and Repair of Fender System	-	0	$113.06	0	$0.00
3364	Replace / Construct Fender System	-	0	$ 94.38	0	$0.00
3366	Drift and Debris Removal	4	176	$ 40.60	176	$7,145.60
3368	Installation and Replacement of NBIS Pipes and Culverts	-	0	$469.04	0	$0.00
3370	Maintenance and Repair of NBIS Pipes and Culverts	-	0	$250.05	0	$0.00
3372	Bridge Installation & Replacement	-	0	$ 56.53	0	$0.00
3374	Repair and Maint of Pedestrian Bridges	-	0	$ 35.12	0	$0.00
3376	Clean/Wash Bridge Decks	-	0	$ 0.05	0	$0.00
	Total	**267**	**11,413**		**246,721**	**$ 1,246,853.41**
				Normilized Cost		**$ 1,664.69**

Table A.5: Cost data of recommended maintenance for bridges flagged, but not scheduled for replacement

	Recommended Maintenance					
Maintenance Number	Maintenance Type	Number of Cases	Quantities	Average Cost	Total Area or LF	Total Cost By Quantity
3304	Maintain/Replace Timber Superstructure Components	217	17959	$ 111.58	6385	$2,003,865.22
3306	Maintain Concrete Superstructure Components	73	3066	$ 132.19	178290.079	$405,294.54
3308	Maint. Of Steel Plate Bridge Joints	-	0	$ 114.80	0	0
3310	Maintenance/Repair/Replacement of Standard Bridge Expansion Joints	58	1262	$ 23.60	7650	$29,783.20
3312	Maint/Replace/Repair Modular Bridge Joints	-	0	$ 125.56	0	$0.00
3314	Maintain Steel Superstructure Components	430	119930	$ 196.60	594035.207	$23,578,238.00
3316	Maint to Timber Handrail	515	12362	$ 12.41	18608	$153,412.42
3318	Maint to Concrete Handrail	115	3100	$ 192.05	10509	$596,750.00
3320	Maint to Aluminum Handrail	-	0	$ 84.58	0	$0.00
3322	Maint to Steel Handrail	59	2628	$ 39.90	4560	$104,857.20
3324	Maint / Repair / Replace Timber Deck Components	506	59454	$ 36.29	371347.878	$2,157,585.66
3326	Maintain Concrete Deck	141	89002	$ 25.20	366401.965	$2,242,850.40
3328	Maintenance/Repair/ Replace Steel Plank Bridge Floor	20	7151	$ 56.64	70393.239	$405,032.64
3330	Maintenance/Repair Open Grid Steel Floor	-	0	$ 102.94	0	$0.00
3332	Maint Drainage System - Bridge	4	335	$ 2.42	403	$810.70
3334	Bridge Bearings	345	4144	$ 218.46	4124	$905,298.24
3336	Moveable Bridges (Maintenance)	-	0	$ 40.20	0	$0.00
3342	Clean and Paint Structural Steel	439	500740	$ 7.18	616633.472	$3,595,313.20
3344	Repair / Replace Timber Substructure Components	497	10679	$ 214.70	20676	$2,292,781.30
3346	Repair / Maintain Timber Wings & Blkhds	443	15672	$ 41.31	354241.512	$647,410.32
3348	Maintain Concrete Substructure Components	239	4443	$ 209.91	16842	$932,630.13
3350	Maint R C Wings and Walls	207	3974	$ 121.50	368584.987	$482,841.00
3352	Maint Slope Protection	22	2589	$ 14.89	33030.234	$38,550.21
3354	Maintain Steel Substructure Components	67	1133	$ 273.54	6631	$309,920.82
3362	Maintenance and Repair of Fender System	-	0	$ 113.06	0	$0.00
3364	Replace / Construct Fender System	-	0	$ 94.38	0	$0.00
3366	Drift and Debris Removal	21	219	$ 40.60	219	$8,891.40
3368	Installation and Replacement of NBIS Pipes and Culverts	-	0	$ 469.04	0	$0.00
3370	Maintenance and Repair of NBIS Pipes and Culverts	19	126	$ 250.05	472	$31,506.30
3372	Bridge Installation & Replacement	-	0	$ 56.53	0	$0.00
3374	Repair and Maint of Pedestrian Bridges	-	0	$ 35.12	0	$0.00
3376	Clean/Wash Bridge Decks	45	7677	$ 0.05	36471.932	$383.85
	Total	**4,482**	**867,645**		**3,086,510**	**$ 40,924,006.75**
				Normilized Cost		**$ 54,638.19**

APPENDIX B: COMPLETE COPIES OF SURVEY

Figure B.1: Initial Survey 1

Tab 1: Instruction Page

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

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: Direct Weighting

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: AHP Questions

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 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		

		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		

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: Mid-Value Splitting

Part 1 - 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 you would be with an improvement in the condition rating from X to 9?

Options:

1 2 3 4 5 6 7 8

Answer:

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 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 condition
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 condition from 0 to X, as you would be in improvement in deck condition rating X to 9?

Options:

[redacted]

Answer:

Deck Condition Rating - Question 4

Consistency check: In general, are you equally satisfied with an deck condition 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 superstructure condition
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 superstructure condition
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 superstructure condition 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 condition 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.

Substructure Condition

Substructure Condition Rating - Question 1

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

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 a substructure condition 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.

Figure B.2: Recommended Survey 1

Tab 1: Instructions

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 - Maintenance AHP Questions

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: Direct Weighting

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	10
	Superstructure Condition Rating	10
	Substructure Condition Rating	10
Vulnerability	Scour Vulnerability	
	Fracture Critical Vulnerability	
	Overload Vulnerability	
Economic Vitality	Detour Length	4
Freight Mobility	Truck Volume (ADTT)	4
	Truck Volume / Capacity	4
	Distance to Freight Terminal	4
Functionality	Clear Deck Width Priority	6
	Vehicle Clearance Priority	6
Maintenance Needs	Cost of Priority Maintenance Needs	
	Cost of Recommended Maintenance Needs	
Maintenance Burden	Total Cost of Maintenance Performed	
	Total Cost of Reoccurring Maintenance	

Percent Left	42
Total	58

Tab 3: AHP Questions

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	Maintenance Needs	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 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	Maintenance Needs		
Infrastructure Condition	Maintenance Burden		
Infrastructure Condition	Vulnerability		
Infrastructure Condition	Economic Vitality		
Infrastructure Condition	Freight Mobility		
Infrastructure Condition	Functionality		
		More Important Goal	Degree of Importance
Maintenance Needs	Maintenance Burden		
Maintenance Needs	Vulnerability		
Maintenance Needs	Economic Vitality		
Maintenance Needs	Freight Mobility		
Maintenance Needs	Functionality		
Maintenance Needs	Infrastructure Condition		

		More Important Goal	Degree of Importance
Maintenance Burden	Maintenance Needs		
Maintenance Burden	Vulnerability		
Maintenance Burden	Economic Vitality		
Maintenance Burden	Freight Mobility		
Maintenance Burden	Functionality		
Maintenance Burden	Infrastructure Condition		

		More Important Goal	Degree of Importance
Vulnerability	Infrastructure Condition		
Vulnerability	Maintenance Needs		
Vulnerability	Maintenance Burden		
Vulnerability	Economic Vitality		
Vulnerability	Freight Mobility		
Vulnerability	Functionality		

		More Important Goal	Degree of Importance
Economic Vitality	Infrastructure Condition		
Economic Vitality	Vulnerability		
Economic Vitality	Freight Mobility		
Economic Vitality	Maintenance Needs		
Economic Vitality	Maintenance Burden		
Economic Vitality	Functionality		

		More Important Goal	Degree of Importance
Freight Mobility	Infrastructure Condition		
Freight Mobility	Vulnerability		
Freight Mobility	Economic Vitality		
Freight Mobility	Maintenance Needs		
Freight Mobility	Maintenance Burden		
Freight Mobility	Functionality		

		More Important Goal	Degree of Importance
Functionality	Infrastructure Condition		
Functionality	Vulnerability		
Functionality	Economic Vitality		
Functionality	Freight Mobility		
Functionality	Maintenance Needs		
Functionality	Maintenance Burden		

Part 2: Performance Measures

Item A	Item B	More Important	Degree of Importance

Deck Condition	Superstructure Condition Rating		
Deck Condition	Substructure Condition Rating		
		More Important Measure	Degree of Importance
Superstructure Condition Rating	Deck Condition		
Superstructure Condition Rating	Substructure Condition Rating		
		More Important Measure	Degree of Importance
Substructure Condition Rating	Deck Condition		
Substructure Condition Rating	Superstructure Condition Rating		
		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
Clear Deck Width Priority	Vehicle Clearance Priority		

		More Important Measure	Degree of Importance
Cost of Priority Maintenance	Cost of Recommended Maintenance		

		More Important Measure	Degree of Importance
Total Cost of Maintenance Performed	Total Cost of Reoccurring Maintenance		

Tab 4: Maintenance AHP Questions

Bridge Prioritization, Maintenance Burden : 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
Repair / Replace Timber Substructure	Maintain Timber Superstructure Components	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	Maintenance Actions are equally important
2	Maintenance Action is slightly more important
3	Maintenance Action is moderately more important
4	Maintenance Action is strongly more important
5	Maintenance Action is extremely more important

Maintenance Needs

Item A	Item B	More Important	Degree of Importance
Repair / Replace Timber Substructure	Maintain Timber Superstructure Components		
Repair / Replace Timber Substructure	Maintain Steel Superstructure Components		
Repair / Replace Timber Substructure	Maintain Concrete Superstructure Components		
Repair / Replace Timber Substructure	Maintain Concrete Substructure Components		

Repair / Replace Timber Substructure	Maintain Concrete Deck		

		More Important Measure	Degree of Importance
Maintain Timber Superstructure Components	Maintain Steel Superstructure Components		
Maintain Timber Superstructure Components	Maintain Concrete Superstructure Components		
Maintain Timber Superstructure Components	Maintain Concrete Substructure Components		
Maintain Timber Superstructure Components	Maintain Concrete Deck		
Maintain Timber Superstructure Components	Repair / Replace Timber Substructure		

		More Important Measure	Degree of Importance
Maintain Steel Superstructure Components	Maintain Concrete Superstructure Components		
Maintain Steel Superstructure Components	Maintain Concrete Substructure Components		
Maintain Steel Superstructure Components	Maintain Concrete Deck		
Maintain Steel Superstructure Components	Repair / Replace Timber Substructure		
Maintain Steel Superstructure Components	Maintain Timber Superstructure Components		

		More Important Measure	Degree of Importance
Maintain Concrete Superstructure Components	Maintain Concrete Substructure Components		
Maintain Concrete Superstructure Components	Maintain Concrete Deck		
Maintain Concrete Superstructure Components	Repair / Replace Timber Substructure		
Maintain Concrete Superstructure Components	Maintain Timber Superstructure Components		
Maintain Concrete Superstructure Components	Maintain Steel Superstructure Components		

		More Important Measure	Degree of Importance
Maintain Concrete Substructure Components	Maintain Concrete Deck		
Maintain Concrete Substructure Components	Repair / Replace Timber Substructure		
Maintain Concrete Substructure Components	Maintain Timber Superstructure Components		

Maintain Concrete Substructure Components	Maintain Steel Superstructure Components		
Maintain Concrete Substructure Components	Maintain Concrete Superstructure Components		

		More Important Measure	Degree of Importance
Maintain Concrete Deck	Repair / Replace Timber Substructure		
Maintain Concrete Deck	Maintain Timber Superstructure Components		
Maintain Concrete Deck	Maintain Steel Superstructure Components		
Maintain Concrete Deck	Maintain Concrete Superstructure Components		
Maintain Concrete Deck	Maintain Concrete Substructure Components		

Maintenance Burden			
Item A	**Item B**	**More Important**	**Degree of Importance**
Repair / Replace Timber Substructure	Maintain Steel Superstructure Components		
Repair / Replace Timber Substructure	Maintain Concrete Deck		
Repair / Replace Timber Substructure	Maintain Timber Deck Components		

		More Important Measure	Degree of Importance
Maintain Steel Superstructure Components	Maintain Concrete Deck		
Maintain Steel Superstructure Components	Maintain Timber Deck Components		
Maintain Steel Superstructure Components	Repair / Replace Timber Substructure		

		More Important Measure	Degree of Importance
Maintain Concrete Deck	Maintain Timber Deck Components		
Maintain Concrete Deck	Repair / Replace Timber Substructure		
Maintain Concrete Deck	Maintain Steel Superstructure Components		

		More Important Measure	Degree of Importance
Maintain Timber Deck Components	Repair / Replace Timber Substructure		
Maintain Timber Deck Components	Maintain Steel Superstructure Components		
Maintain Timber Deck Components	Maintain Concrete Deck		