THESIS

DETERMINING THE ITEMS THAT STRUCTURE BRIDGE MANAGEMENT COMPONENTS AND THEIR RELATIVE WEIGHTS

Submitted by

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ABSTRACT

DETERMINING THE ITEMS THAT STRUCTURE BRIDGE MANAGEMENT COMPONENTS AND THEIR RELATIVE WEIGHTS

Ensuring the optimal allocation of available resources between competing bridges is difficult, especially when considering a combination of factors such as continual age related deterioration, ever-increasing traffic demands, and limited resources to address preservation and improvement needs. Optimally allocating funding is crucial since bridges are an essential and expensive component of transportation networks.

Bridge Management Systems (BMSs) are commonly used tools that aid managers and decision makers in establishing methods for optimizing available resources and determining how to distribute funds between competing bridges. Recently, *NCHRP Synthesis 397Bridge Management Systems for Transportation Agency Decision Making* investigated how transportation agencies are using BMSs and the current state of bridge management practices. The report identified concerns of inadequacy and ineffectiveness with bridge management practices that base decisions solely on single value assessments such as Pontis' Bridge Health Index or the Sufficiency Rating, as found in the federally mandated National Bridge Inspection Standards. Given the critiques in the NCHRP report and other literature related to bridge management, it is evident there exists a need to pursue and develop alternative bridge management practices and systems.

The overall purpose of this research is to investigate the concept of isolating the items used to make up a single rating or index in an effort to categorize them under distinct bridge

management components such as structural condition, impact on public, and hazard resistance. Each bridge management component has a defined objective as follows:

- Structural Condition - accurately access the structural adequacy of a bridge.
- Impact on Public - evaluate how bridge attributes affect the traveling public.
- Hazard Resistance - evaluate how bridge attributes and external factors affect the vulnerability of a bridge concerning the probability of an extreme event as well as the probability of failure during that event.

The specific objectives of this research are (i) to identify the appropriate items that make up each of the aforementioned components and (ii) to determine the relative importance of those items as represented by weighting factors. To achieve these objectives, the researcher conducted a two-part survey seeking input from key bridge management personnel from State DOTs, the Federal Highway Administration (FHWA), and other industry professionals and experts. The first part of the survey identified the appropriate items and the second part determined the relative importance of those items using a mathematical method called the Analytic Hierarchy Process (AHP).

The primary contribution of this research is to provide bridge management engineers and decision-makers with effective bridge management components, with well-defined objectives and related items, which clearly identify and distinguish differences in bridge attributes that may go unnoticed when using a single rating or index. This will especially be useful for State DOTs and local agencies, like the Wyoming Department of Transportation, from which the motivation for this research was adapted, who are developing BMSs and methods customized to their particular needs. Upon establishing the bridge management components, by determining the items that make up the components and their relative weights, transportation agencies may utilize them in a variety of ways to conduct multi-criteria decision analyses that complement their current bridge management practices, which in turn may better illustrate the operation of bridges in their system.

The total number of respondents was 47, of which 32 were from 29 different State transportation agencies. Of the 47 participants, only 27 contributed to the second part of the survey. A major finding of this research was a result of several participant remarks about with quantifying preservation and maintenance demands through the addition of a fourth bridge management component. The preservation and maintenance component encompasses items that are bridge elements, but may not contribute to the structural capacity of a bridge. Given the degree of influence of adding a fourth component, further research is recommend to confirm these findings and conclusions with a refined two-part survey similar to this research study and possibly interviews or focus groups.

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DEDICATION

To my three wonderful children ... Jill, Daniel and Abbie, all of you have undoubtedly enriched my life. I love you very much!

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CHAPTER 1: INTRODUCTION

This chapter provides a brief background discussion on the current state of bridge inspection practices and bridge management. In addition, this chapter introduces the problem statement along with the corresponding research questions, and concludes with the motivation and purpose of this research.

1.1 BACKGROUND

Optimally allocating resources in order to maintain a safe transportation system is a key objective of many transportation agencies. This is especially true under the current economic environment of fixed or reduced revenue streams. A recent article in the American Association of State Highway and Transportation Officials (AASHTO) Journal discussed this point through the testimonies of representatives from several State Departments of Transportation (DOTs) to the U.S. Department of Transportation (USDOT). DOT representatives stated that the transportation system is severely underfunded and that "legislation should provide adequate sources of revenue to pay for replacing or repairing deteriorating and congested roads, bridges, and transit systems" (AASHTO, 2010, p. 1). Many of the funding concerns are a result of the Federal fuel tax not being increased or adjusted for inflation since 1993 (AASHTO, 2010). Fuel taxes support the Highway Trust Fund, which in turn provides the capital for highway projects. However, since there has not been an increase in fuel taxes since 1993, the Highway Trust Fund has not been able to keep up financially with the needs and demands of the nation's aging transportation system. Jack Basso of AASHTO stated (AASHTO, 2010, p. 2):

"The Federal government has had to transfer money to the Highway Trust Fund to meet basic maintenance needs. States are also beginning to dip into general funds for transportation projects. If no new cash is found, current levels of Federal transportation funding will be cut in half in Fiscal Year 2012."

Construction and maintenance costs have continued to rise over the last decade (as illustrated in Figure 1) and when combined with the aforementioned decline in revenue, the result is a reduction in purchasing power (as shown in Figure 2). This makes it difficult for a transportation agency to maintain, much less improve, their transportation networks.

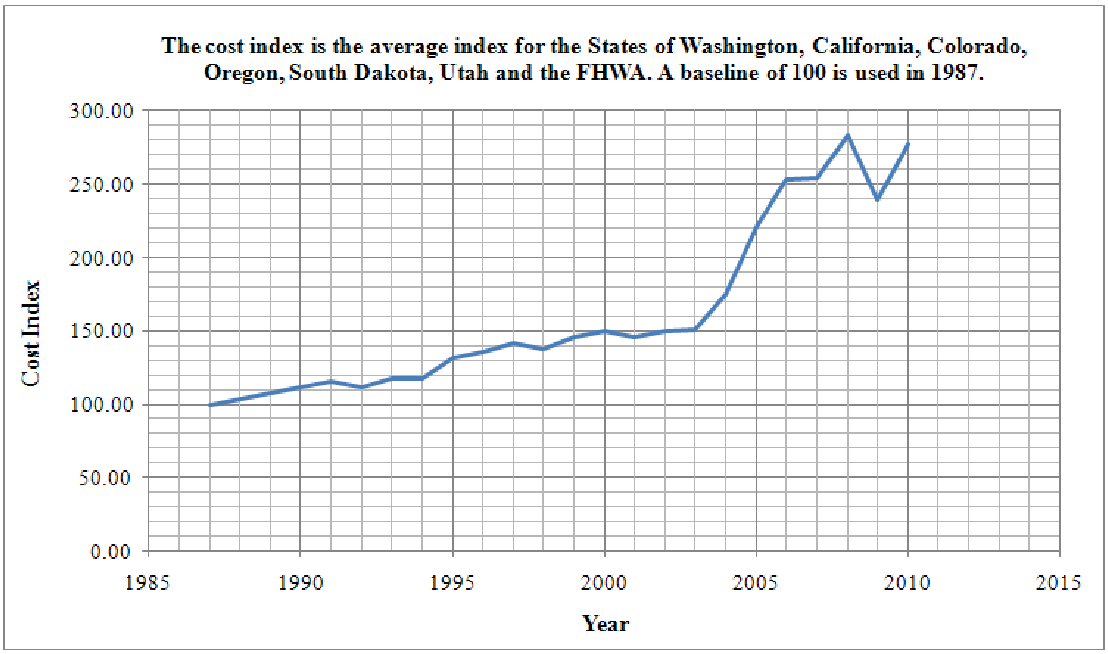

Figure 1: Construction Cost Index from 1987 through Mid-2010 (WSDOT, 2010)

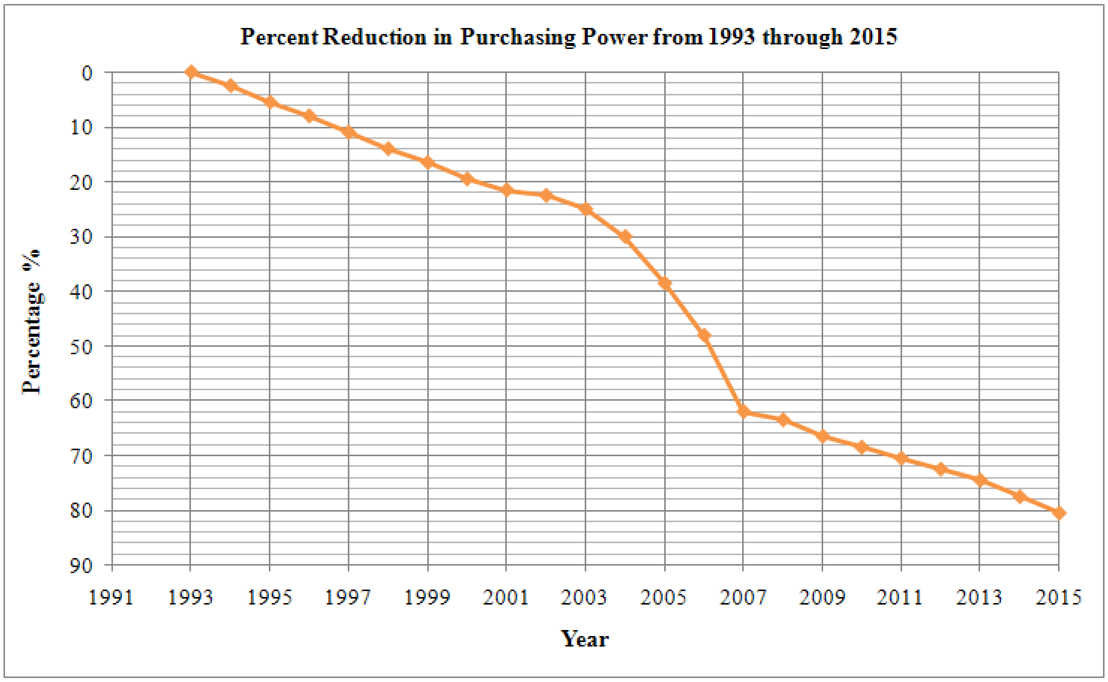

Figure 2: Purchasing Power (AASHTO, 2009)

In addition to increases in the cost of construction and available funding decreasing, the capacity demand on National Highway System (NHS) continues to increase. The NHS is a part of the total highway system and "includes the Interstate System as well as other routes most critical to national defense, mobility, and commerce" (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008, pp. 2-23). It makes up about 4% of the miles of the total highway system, but carries about 45% of the total Vehicle Miles Traveled (VMT) (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008). Furthermore, from 1995 through 2004 the volume of traffic on the interstate highways increased by approximately 28% and the heavy truck traffic on those highways has nearly doubled in the last 20 years and is expected to double again by the year 2035 (AASHTO, 2008). Such a high traffic volume, specifically heavy truck traffic, puts a tremendous amount of strain on an ageing transportation network.

A significant increase in VMT and natural deterioration combined with a gap in funding results in a steady decline in the condition of Nation's transportation system. Construction of a majority of the national interstate system occurred approximately 50 years ago. A vital and expensive element of transportation networks are bridges. The "period of time on which the statistical derivation of transient loads is based" (AASHTO, 2010, pp. 1-2) defines the design life of a bridge. Per the *AASHTO LRFD Bridge Design Specifications*, the design life is 75 years, placing a large number of bridges in the last stage of their theoretical design life, as illustrated in Figure 3 and Figure 4. Additionally, Figure 3 shows that the number of bridges that are either Structurally Deficient[1] or Functionally Obsolete[2] increase in correlation with their age, and thus the maintenance and rehabilitation needs increase as well. Structurally Deficient and Functionally Obsolete, defined in the federally mandated National Bridge Inspection Standards (NBIS) as discussed in more detail in Chapter 2, respectively describe a bridge's structural integrity and its effectiveness concerning current design and safety standards.

[1]A bridge is Structurally Deficient if the NBIS condition rating of item 58, 59, 60 or 62 has a value of 4 or less, or if the NBIS appraisal rating of item 67 or 71has a value of 2 or less as seen in Table 6.

[2]A bridge is Functionally Obsolete if the NBIS appraisal rating of item 68, 69, or 72 has a value of three or less, or if item 67 or 71 have a value of three as seen in Table 7.

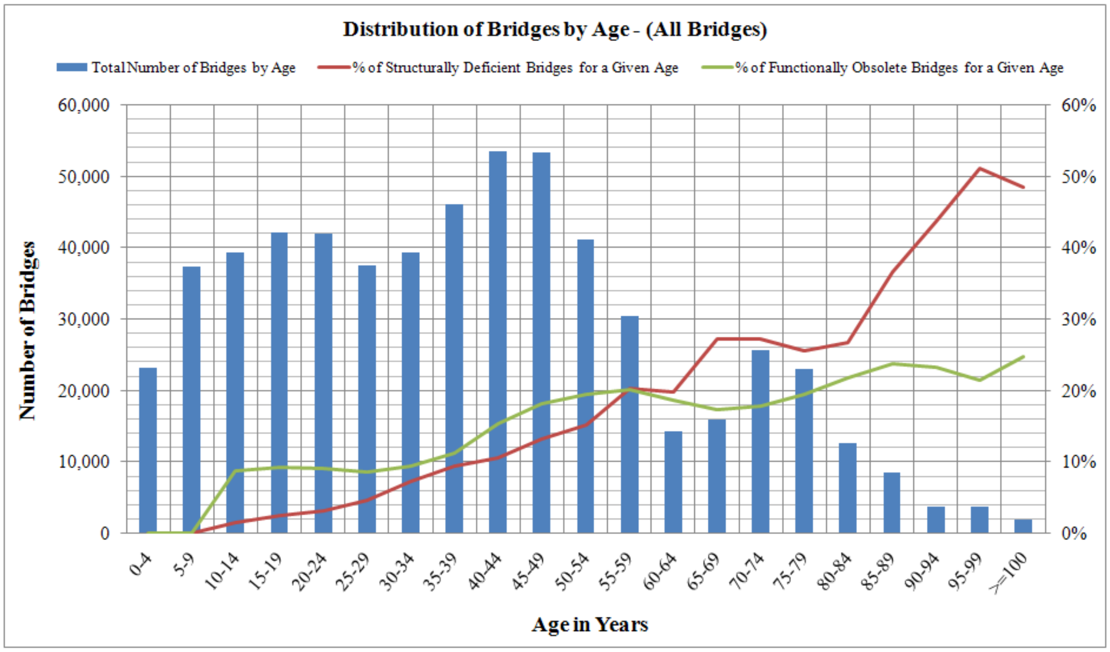

Figure 3: Age of Bridges as of December 31, 2009 (FHWA, 2010)

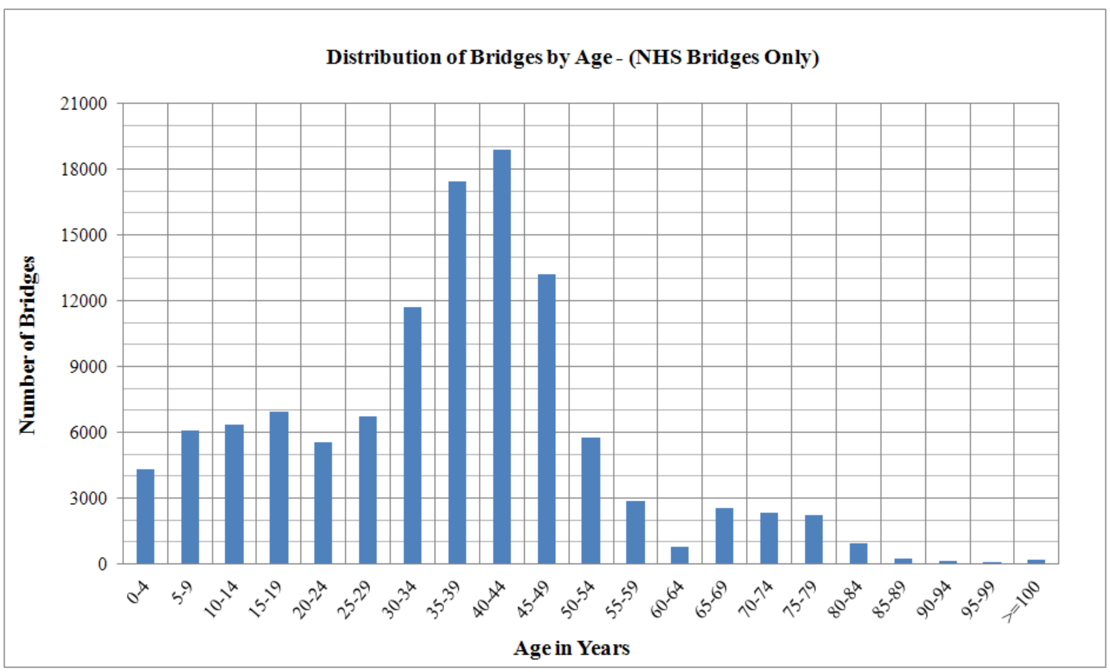

Figure 4: Age of NHS Bridges as of December 31, 2006 (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008)

Establishing a method that optimally allocates resources for maintenance, rehabilitation and replacement of bridges is especially important since they are an essential and expensive component of the NHS. With limited funds, a greater demand for use, and a transportation system that continues to deteriorate with age, it is crucial that transportation agencies have an effective decision-making process and available tools to manage their network of bridges.

1.2 BRIDGE INSPECTION

In order to make well-informed decisions about the allocation of resources between competing bridges, it is imperative that decision-makers know the condition and recognize characteristics of the bridges they oversee. Currently all 50 states use the National Bridge Inspection Standard (NBIS) to determine and record bridge condition and characteristic information. The NBIS provide a standard format for the inspection and recording of bridges, and encompasses a large range of structure types (steel girder, concrete girder, timber, etc.) and functions (river crossings, railroad crossings, overpasses, etc.). Using this standard system provides a level of consistency in inspection and recording between states across the nation, however it "depends on the skill and training of the certified bridge inspectors" (FHWA). The regulatory Federal code that governs the NBIS is Title 23, part 650, subpart C (23 CFR 650C). Chapter 2 provides more information about the NBIS, National Bridge Inventory (NBI), the current state of bridge management, and how the Federal Highway Administration (FHWA), State DOTs and other local agencies that own and are responsible for the inspection of bridges currently utilize them.

Each State has a transportation department or agency that inspects and manages both on-system and off-system bridges within its State. The outlined distinction between on-system and off-system varies between agencies, but in general on-system bridges are bridges owned by the State itself (i.e. interstate bridges) and off-system bridges are bridges owned by other local government agencies such as counties and municipalities. It is ultimately the responsibility of the State agency to ensure that both on-system and off-system structures meet Federal requirements using the NBIS and to report inspection results to the FHWA by means of the NBI. The FHWA uses those inspection results, by means of the Sufficiency Rating, to allocate funding for construction of new bridges as well as maintenance and rehabilitation of existing bridges. Appendix B of the FHWA *Recording and Coding Guide* defines the Sufficiency Rating as "a method of evaluating highway bridge data by calculating four separate factors to obtain a numeric value which is indicative of bridge sufficiency to remain in service" (FHWA, 1995, pp. B-1). Chapter 2 includes a more in depth discussion on the Sufficiency Rating. Bridge section managers, maintenance engineers, and other stakeholders determine and rank bridge preservation and improvement work based inspection data. Their decisions and rankings are established using several items that include, but are not limited to the structural condition, impact to the user if the structure were out of service, its vulnerability to hazards, available funding, and the strategic plan of the DOT (Markow & Hyman, 2009).

NCHRP Synthesis 397 discusses how the recent collapse of the I-35W Bridge in Minneapolis made transportation agencies across the country scrutinize how they inspect, manage, and fund bridges in their transportation network. Accuracy and reliability of bridge inspection reports is a specific issue that generated debate about agencies adopting a new way of inspecting and reporting the current structural condition of a bridge. In addition, the report notes a lack of understanding of what it means when a bridge is classified as Structurally Deficient or Functionally Obsolete and how that relates to the safety of the traveling public (Markow & Hyman, 2009).

1.3 BRIDGE MANAGEMENT

A primary objective in bridge management is to ensure the optimal allocation of resources particularly when bridges in a transportation network are continuing to deteriorate and available resources to address preservation and improvement needs are limited. Determining the most beneficial allocation of resources is challenging; a common tool used by decision makers to help in making critical decisions is a Bridge Management System (BMS).A BMS is defined by the FHWA as "a system designed to optimize the use of available resources for the inspection, maintenance, rehabilitation and replacement of bridges" (FHWA, 1995, p. x). Furthermore, a BMS serves as a computerized tool that interfaces with a database that contains information about the current condition and related characteristics of all bridges on a transportation network. The previously mentioned routine inspections gather condition and characteristic information. A BMS helps the user interpret data so he/she is able to determine how to best allocate available resources for the maintenance, rehabilitation and replacement needs of several structures within the network.

NCHRP Synthesis 397 recently reviewed current bridge management practices; and investigated how transportation agencies utilize BMSs to make decisions about bridges on their transportation network. The report portrays the vital role bridges have on a transportation system and the importance of comprehensive asset/bridge management. Bridges are essential since they provide crossings at locations where an alternative route would result in an inconvenience for the user, potentially adding considerable travel time and cost. Additionally, the report notes that the maintenance, rehabilitation and replacement of bridges is very costly and thus the financial decisions made to improve the structural condition and/or the serviceability of a bridge is of the utmost importance, not only to account for available funds but also to ensure a safe and effective transportation system (Markow & Hyman, 2009).

Presently, the most well-known BMS licensed to many DOTs and other organizations is the Pontis BMS. Originally developed by the FHWA, the Pontis program is now owned, administrated, and maintained by AASHTO. A recent FHWA case study provides an overview of bridge management practices for California, Florida, and South Dakota;

specifically how they integrate and utilize the Pontis BMS (FHWA, 1995). Through a bridge health index (BHI), cost benefit analysis and generation of scenarios, Pontis is able to aid decision makers in selecting the best option from several investment alternatives that ensures the maximum return. A BHI is an economic indicator that measures how much asset value elements of the structure have depreciated as their structural condition has deteriorated over time. Values of a BHI range from 0% to one 100% with 0% representing the worst condition and 100% indicating that the structure still has 100% of its original asset value (a like new condition). Maintenance repairs conducted on the element of interest increases its asset value, and thus increases the BHI of the bridge. However, many transportation agencies do not take full advantage of the program's capabilities. They simply use it as a database, storing bridge inventory and inspection data, or as one of several other applications as seen in Figure 5.

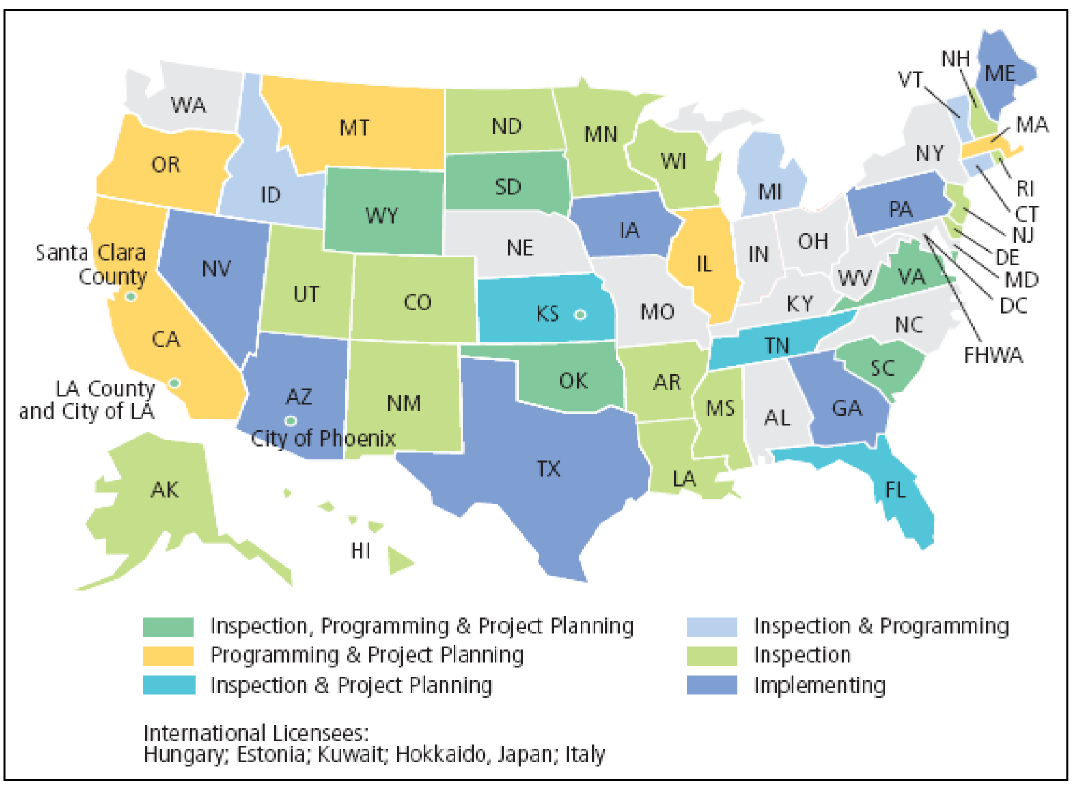

Figure 5: Pontis Licenses for 2005 (FHWA, 2005)

The goal of the FHWA report is to "encourage more states to move to the next level in using the software [Pontis] to its full extent" (FHWA, 2005, p. 28). It is evident from the usage presented in Figure 5 that there is hesitation by many Pontis users to rely solely on the BHI for asset management and decision making analysis. See Chapter 2 for a more in-depth discussion on Pontis and the BHI.

In addition to the BHI, there are concerns among some bridge managers about the ineffectiveness of the NBIS Sufficiency Rating for the reason that an agency can allocate funds to improve a bridge's structural condition, and yet not realize a benefit from that investment concerning the rating. In other words, an agency can spend money on repairs or preventive maintenance and see little if any change in the Sufficiency Rating.

The following example illustrates how a bridge owner may not realize a return on their investment when solely looking at the Sufficiency Rating. Typically, bridge rehabilitations may include the replacement or repair of several bridge elements such as expansion joints, approach slabs, bearings, and bridge railing. However, the FHWA *Recording and Coding Guide* clearly states that these elements shall not be considered when performing a condition evaluation (FHWA, 1995).Therefore, they are not included in the NBIS condition rating, which in turn is used to calculate the Sufficiency Rating (Hearn, Cavallin, & Frangopol, 1997). Assume the rehabilitation of a bridge involved the replacement or repair of the aforementioned elements that cost $100,000 to complete. Because the elements are not included in the NBIS condition rating, the considerable amount of money invested by the agency to improve the bridge's structural condition will not affect the Sufficiency Rating. An AASHTO meeting in May 2008 echoes this sentiment, where one of the stated visions for future in bridge management is to improve the calculation of the Sufficiency Rating through refined elements and inclusion of more risk factors (Johnson, 2008).

In light of these issues, some State DOTs and local governments have developed their own BMS to aid in decision making. The City and County of Denver is in the process of developing the Denver Bridge Health Index (DBHI), which is similar to the BHI generated by Pontis, but better represents the needs of their comparatively small network of bridges with an adjustment in the calculations. It is the hope of the City and County of Denver that the newly developed DBHI will more accurately represent and model the condition of the bridge than the Pontis BHI does (Jiang & Rens, 2010). Chapter 2 includes further discussion on the DBHI and the Pontis BHI.

Alabama has developed the Alabama Bridge Information Management System (ABIMS) that utilizes a large database of bridge inventory and inspection data. The system allows the user to select from a variety of different database queries to generate reports. A report unique to their system is the Deficiency Point calculation, which is similar to the Sufficiency Rating, but allows the user to specify a particular deficiency such as load, vertical clearance, structure width, and condition. Potential basis for Deficiency Points include traditional AASHTO loadings, such as the national truck and lane loads in the AASHTO LRFD design specification, or some user defined loading (Markow & Hyman, 2009).

The Wyoming Department of Transportation (WYDOT) is considering using a two-dimensional BMS, which is where the motivation for this research was adapted. A two-dimensional BMS is similar to the Sufficiency Rating or a BHI in that it utilizes NBIS items[3] and AASHTO Commonly Recognized (CoRe) elements[4], but it looks at the structural condition, functionality and risk of a bridge separately rather than lumping them together to obtain a single rating. Looking at structural condition, functionality and risk independently

[3]Elements and characteristics used to inspect bridges as defined by the code of federal regulations (23 CFR 650C), also known and the NBIS, are known as NBIS items.

[4] CoRe elements are a breakdown of major bridge elements (e.g. deck, superstructure and substructure) into minor elements (e.g. girders, bearings, columns, piles, etc.) that make up the major elements.

may aid WYDOT managers in making funding decisions and setting the frequency of inspections (Fredrick, 2010).

Easily recognizing these variations among structures helps decision makers allocate resources and prioritize work between bridges competing for those resources.

1.4 Problem Statement

Given the previous discussion and as supported by the following statement, it is clear that a decision process that only involves a single rating, such as the Sufficiency Rating or a BHI, to manage bridges is inadequate (Markow & Hyman, 2009, p. 15).

> "The NBI database and the computed [Structurally Deficient] SD, [Functionally Obsolete] FO, and [Sufficiency Rating] SR ratings have provided current and comprehensive data on bridge status and investment needs during the last 35 years. … however … Sufficiency Ratings are recognized to have shortcomings when applied to management or funding decisions."

The current set of criteria used by the FHWA to determine if a bridge is eligible for Highway Bridge Program (HBP) funding is the code of Federal regulations - 23 CFR 650.409. These criteria include (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA)., 2006):

- The bridge must have a Sufficiency Rating of 80 or less and be classified as either Structurally Deficient or Functionally Obsolete.
- Bridges with a Sufficiency Rating between 50 and 80 are eligible and can use funds for rehabilitation only, while those with a Sufficiency Rating of less than 50 are eligible for replacement funding.
- The structure must span greater than 20 feet, and cannot have had major repairs or reconstruction within the past 10 years.

These requirements based on the Sufficiency Rating provide a way for the FHWA to assign funding priorities to bridges. In theory, bridges with a lower rating will get funding first because they are in the "poorest" condition. However, simply having a lower Sufficiency Rating does not necessarily mean a bridge is in “worse” condition and needs maintenance, rehabilitation or replacement first. For example, if a bridge has a long detour length and high average daily traffic (ADT) the Sufficiency Rating may be low even if it is in good structural condition. This is evident to some bridge managers who feel that using a single number such as the Sufficiency Rating or BHI is not necessarily the best way to prioritize structures, especially when they are competing for limited funds. The following statement made in a recent study on bridge management practices (Markow & Hyman, 2009, p. 18) underscores this point:

> “This form of bridge management [based on NBI data] utilizes aggregated information and thus has limited applicability for analytical decision making. While the formula is convenient for funds allocation, it is not necessarily sufficient for analysis and needs prediction.…A new form of bridge management decision support to facilitate budgeting, policy analysis and project programming [came to be] desired.”

A statement in a recent paper about BHI (Jiang & Rens, 2010, p. 581) also cites the Sufficiency Rating issue:

> “An overall SR based on National Bridge Inspection Standards data was used as a performance measure at the Federal level for funding allocation, but this measure emphasized large-scale functional and geometric characteristics of bridges, making it irrelevant for maintenance decision-making”

NCHRP Synthesis 397 summarized some concerns presented in congressional testimony as follows (Markow & Hyman, 2009):

- The classifications of Structurally Deficient or Functionally Obsolete are overly broad because they only indicate that the bridge has flaws and do not differentiate between the specific elements that are causing the inadequacy with those that are still acceptable; nor do they account for the potential impact of the deteriorating elements.
- An agency can spend money on preventative measures without seeing a marked improvement in the Sufficiency Rating (as discussed in section 1.3 Bridge Management).

- Investigation and research promote the continually updating of design specifications, construction methods, materials, and other factors, while the methodology to calculate a Sufficiency Rating has been the same for over 15 years.
- The Sufficiency Rating does not adequately account for a bridge deck that is in poor condition.
- Transportation agencies customize BMSs and predictive models for their specific requirements. In other words, there is no general, widely used BMS or model for tracking performance of bridge rehabilitation and replacement investments and needs, deterioration trends, trade-off analysis and cost-benefit analysis.

In conclusion, solely using a single value rating or index to manage bridges is ineffective, suggesting a need exists to pursue and develop alternative bridge management practices and systems.

1.5 Purpose of Research and Research Questions

The purpose of this research is to investigate the concept of isolating the items used to make up a single rating or index (i.e. Sufficiency Rating or Bridge Health Index) in common BMSs in an effort to categorize them under distinct bridge management components (i.e. Structural Condition, Impact on Public and Hazard Resistance) and to determine the relative importance associated with each item and component as represented by weighting factors. In addition to the primary purpose stated, this research will also determine the relative importance of the components. Having isolated bridge management components allows for a straightforward approach in detecting differences among structures, which in turn may help decision-makers in developing BMSs and conducting tradeoff analysis for prioritizing preservation and maintenance work for their network of bridges.

An item can be a major or minor element of a bridge (like deck, girder, column, etc.), a characteristic of the bridge (such as vertical clearance, span length, roadway width, etc.) or an external feature that is associated with the bridge (for example seismic category, detour length, traffic volume, etc.). The weighting factor is simply the relative importance of an item to the other items within the component. The following statement (Michael Baker Jr., Inc., 2009, p. 233) acknowledges the validity of this approach:

> "… there are better ways to present the information gathered from bridge inspections than lumping all the information into one rating number. … relying on a small number of rating values to program work (e.g., the Sufficiency Rating or NBI condition ratings), despite its advantages for descriptive purposes, has severe limitations that would make models based on the approach questionable."

Determining which items are included in a bridge management component requires that each component have a defined objective. Objectives for the three components are as follows:

- Structural Condition - accurately access the structural adequacy of a bridge.
- Impact on Public - evaluate how bridge attributes affect the traveling public
- Hazard Resistance - evaluate how bridge attributes and external factors affect the vulnerability of a bridge concerning the probability of an extreme event as well as the probability of failure during that event.

The correlated research questions are as follows:

1) *What items should be included in each bridge management component?* NBIS items, CoRe elements, and other items determine the Structural Condition, Impact on Public and Hazard Resistance Components of a bridge. What items would experts in the field of bridge management determine are necessary for each component?
2) *What is the appropriate relative weighting factor of each item?* Weighting factors define each item's relative importance under its respective component.

How would experts in the field of bridge management weigh the previously determined items?

3) *What is the appropriate relative weighting factor of each bridge management component?* Given the defined bridge management components, how would experts in the field of bridge management weight the bridge management components?

Once the items within each bridge management component are identified and their relative weights determined, along with the components' relative weights, transportation agencies may utilize this information in a variety of ways to develop bridge management practices and BMSs, which in turn may address some of the aforementioned concerns by making it easier for a bridge asset manager to assign funding priorities to competing structures, as well as providing a foundation to request additional funding for structures that do not qualify under the current criteria.

1.6 Benefits of Research and Contribution to the Body of Knowledge

The previous sections suggest that there is a general feeling in the field of bridge management about the shortcomings of only utilizing a single rating to manage bridges and that there currently is not a BMS that encompasses the needs of all transportation agencies. With this sentiment there are several bridge managers, agencies, and private companies attempting to develop a BMS that meets their specific needs and is effective at aiding in the decision making process. By breaking down a single rating into multiple components decision makers in the industry would benefit by having another methodology for completing their asset/bridge management analysis. WYDOT, which is currently considering implementation of a two-dimensional BMS as discussed earlier, will be a specific benefactor from this research, as it will provide them with components developed following a mathematical methodology. This will be of particular help when petitioning the FHWA for alternative inspection intervals and when requesting additional funds for maintaining, repairing, and replacing bridges from either the FHWA via HBP funds, or the State legislature (Fredrick, 2010).

Furthermore, there has been recent discussion about changing legislation at the Federal level. The new legislation would be connected to performance and requiring all State DOTs to have a BMS in place. The legislative bills are H.R. 1682 on 3/24/2009 and S.1701 on 9/23/2009, both titled Bridge Life Extension Act of 2009 (Library of Congress, 2009). If passed it would require a State to develop and implement a bridge management system that meets certain requirements in order to continue receiving Federal-aid highway funding. If this occurs this research will be of particular interest for DOTs that do not presently have a BMS in place and are looking for a BMS to implement.

As mentioned earlier there are other BMSs currently in use and under consideration; and this research will provide decision makers with an alternative option, and may show an improvement in performance of bridges on their system that otherwise would not be reflected in the Sufficiency Rating or a BHI.

CHAPTER 2: LITERATURE REVIEW

This chapter presents a comprehensive literature review on current bridge inspection practices, bridge management methodologies and utilized software, and other literature related to this research and bridge management in general.

2.1 BRIDGE SAFETY AND INSPECTION LEGISLATION

The recent collapse of the I-35W Bridge in Minneapolis has brought forth concerns about the safety of the more than 600,000 bridges across the country. The National Transportation Safety Board (NTSB) has investigated six bridge collapses. These include the Silver Bridge in 1967, the I-95 bridge over the Mianus River in 1983, the U.S. Chickasabogue bridge in 1985, the Schoharie Creek bridge in 1987, the Hatchie River bridge in 1989, and the I-35W bridge in 2007 (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008). The catastrophic collapse of bridges' is rare when comparing the number of occurrences to the number of bridges in service across the nation, along with the number of years they have been in service (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008). However, throughout the history of the national transportation system disastrous bridge collapses have prompted the development and refinement of the NBIS. A summary of legislation that has affected bridge inspection and funding is illustrated in Table 1.

Table 1: Bridge Inspection and Funding Legislation (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2004, p. Exhibit 15)

Legislation and Date	Requirements
Federal-Aid Highway Act of1970: (P.L. 91-605)	• Inventory requirement for all bridges on the Federal-aid system • Established minimum data collection requirements

	• Established minimum qualifications and inspector training programs • Established Special Bridge Replacement Program
Surface Transportation Assistance Act of 1978 (P.L. 95-599)	• Provided $4.2 billion for the HBRRP over 4 years • Extended inventory requirement to all bridges on public roads in excess of 6.1 meters • Established Highway Bridge Rehabilitation and Replacement Program (extending funding to Rehab) to replace Special Bridge Replacement Program
Highway Improvement Act of 1982	• Provided $7.1 billion for the HBRRP over 4 years
Surface Transportation and Uniform Relocation Assistance Act of 1987	• Provided $8.2 billion for the HBRRP over 5 years • Added requirements for underwater inspections and fracture-critical inspections • Allowed increased inspection intervals for certain types of bridges
Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA	• Provided $16.1 billion for the HBRRP over 6 years • Mandated State implementation of bridge management systems • Increased funding in HBRRP
National Highway System Designation Act of 1995	• Repealed mandate for management system implementation
Transportation Equity Act for the 21st Century (TEA-21, 1998)	• Provided $20.4 billion for the HBRRP funding over 6 years

Additionally, there has been conversation about the recently proposed Bridge Life Extension Act of 2009 (H.R. 1682 and S.1701), which would require all State transportation agencies to have a BMS in place. The following outline summarizes the specific requirements in the legislation (Library of Congress, 2009):

- <u>Implementation of Highway Bridge Management Systems:</u> As a condition for providing funding assistance to a State, the Secretary shall require the State to develop and implement a bridge management system.

- Applicability to New and Existing Bridges: A highway bridge management system applies to:
    - Design and construction of new bridges
    - Rehabilitation and preventative maintenance of existing bridges
- Preservation of Structures: In developing and implementing a highway bridge management system a State shall:
    - Identify corrosion mitigation and prevention methods that will be used to preserve the highway bridges in the State, taking into account:
        - Material selection
        - Coating considerations
        - Cathodic protection considerations
        - Design considerations for corrosion
        - Concrete requirements
    - Establish a project maintenance program for highway bridges in the State for the purpose of extending the life of each highway bridge
    - Ensure that all highway bridge designers, inspectors, and maintenance individuals implementing the system are trained and certified in corrosion mitigation and prevention techniques
    - Research current inspection technologies and techniques for highway bridges
- Consultation: A State shall carry out the requirements of this paragraph in consultation with engineers and other experts specializing in corrosion mitigation and prevention methods.

2.2 National Bridge Inspection Standards (NBIS)

All State transportation agencies perform inspections on bridges within their State so that they know the condition and recognize characteristics of the bridges they oversee. Agencies conduct inspections using the Federal regulations - 23 CFR 650C, also known and the NBIS. The

NBIS provides an inspection and recording format for a large range of structure types (steel girder, concrete girder, etc.) and functions (river crossings, railroad crossings, etc.) that is consistent between states (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008).

The NBIS requires inspection of all bridges on public roads with a length of 20 feet or more every 24 months. While most inspection frequencies follow this 24-month cycle, the inspection of bridges in poor condition may occur more often, and depending on the situation, some bridges may be inspected every 48 months with FHWA approval. Currently about 83% of bridges are inspected every 24 months, 12% are inspected every 12 months and 5% are inspected on a 48 month cycle (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008). An alternative BMS may be useful in petitioning the FHWA for a 48-month inspection cycle.

The NBIS inspection guidelines are published in the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, FHWA-PD-96-001. The following is an overview of the items discussed in the report and recorded for each bridge as applicable (Markow & Hyman, 2009):

- Items 1–27: General description and administrative information
- Items 28–42: Functional or operational (capacity) information, design load
- Items 43–44: Structure/design/construction type and material of construction
- Items 45–56: Span information, geometric information, and clearance dimensions (no Item 57)
- Items 58–70: Structural condition and bridge loading information
- Items 71–72: Waterway and approach data (no Items 73–74)
- Items 75–97: Inspector's work recommendations and projected costs
- Items 98–116: Other information of various categories

Trained inspectors who document the condition of structural components as well as functional characteristics of the bridge perform required inspections. Major structural elements such as the deck, superstructure and substructure are accessed based on condition ratings, while the appraisal ratings are the basis for the functional characteristics. Given that, bridge ratings are analytically simple and comprehensive; the NBIS is able to encompass an abundant and diverse nationwide bridge population (Markow & Hyman, 2009). Condition and appraisal ratings, as defined in the previously cited FHWA *Recording and Coding Guide*, are discussed in further detail later in this Chapter.

Every year, each State highway department reports the inspection results of the bridges on its transportation network to the FHWA, whom then compiles the data into the National Bridge Inventory (NBI). The NBI database includes the "numbers and percentages of bridges that are listed as Structurally Deficient or Functionally Obsolete… they play a key role in Federal bridge funding and State DOT tracking of bridge condition … a key component of bridge management information" (Markow & Hyman, 2009, p. 11). The principal source for national bridge statistics is the NBI database.

> "Since its inception in the 1970s, the NBI database has compiled a detailed history of every bridge carrying a public highway in the United States, making it the most comprehensive and uniformly organized source of bridge condition data in the country. The NBI data are the basis of FHWA's identification of bridge needs, allocation of bridge program funding, and biennial reporting to Congress (Markow & Hyman, 2009, p. 15)."

In lieu of NBIS items, bridge inspections may utilize the AASHTO CoRe Elements. AASHTO CoRe elements are a breakdown of major bridge elements (deck, superstructure and substructure) to minor elements that collectively form the major elements. For example, minor elements that make up a steel superstructure may include girders, splices and lateral bracing, etc. An agency may prefer to use CoRe elements rather than NBIS items because they provide more detail when collecting data, and thus gives a more accurate and effective analysis when using predictive models and deterioration curves (Markow & Hyman, 2009).

The following is an example where CoRe element data may be used. A steel superstructure has nine steel, W-Beam girders with five girders in good condition and four in poor condition. Furthermore, the sole basis for the superstructure rating is the NBIS, and a cost analysis concluded that it would cost $100,000 to rehabilitate the entire superstructure. However, when using CoRe elements it is clear that only four girders need rehabilitation, not the entire superstructure, and actual rehabilitation cost may only be $40,000.

If an agency opts to use CoRe elements, they must use the FHWA translator program to convert the CoRe element ratings to corresponding NBIS item ratings. For instance, the CoRe element ratings for the girders, splices and lateral bracing are combined into a single superstructure item rating. Conversions are required to enable condition comparisons at a national level, and to help facilitate consistency between State agencies in their reporting to the FHWA (FHWA, 1995).

2.2.1 CONDITION RATINGS

Over time, the materials that make up a bridge will deteriorate causing structural defects. NBIS condition ratings classify these defects. The NBIS items used to indicate the structural condition of a bridge are 58 – Deck, 59 –Superstructure, 60 – Substructure, 61 – Channel and Channel Protection, and 62 – Culverts. It is understood that the first four ratings (58 through 61) apply to bridges and 62 is for culvert evaluation only. Table 2 and Table 3, provided in the *Recording and Coding Guide,* are rating definitions for inspectors when evaluating items 58, 59, and 60 and item 61 respectively.

Table 2: NBIS Condition Ratings, Items 58, 59, and 60 (FHWA, 1995)

CODE	DESCRIPTION
N	NOT APPLICABLE
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION- no problems noted.
7	GOOD CONDITION - some minor problems.
6	SATISFACTORY CONDITION - structural elements show some minor deterioration.
5	FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.

4	POOR CONDITION - advanced section loss, deterioration, spalling or scour
3	SERIOUS CONDITION - loss of section, deterioration, spalling or scour have seriously affected primary structural elements. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	CRITICAL CONDITION - advanced deterioration of primary structural elements. Fatigue cracks in steel, shear cracks in concrete may be present, or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	"IMMINENT" FAILURE CONDITION- major deterioration or section loss present in critical structural elements or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	FAILED CONDITION - out of service - beyond corrective action

Based on descriptions given in Table 2 it is probable that only recently constructed bridges would receive a rating of nine – excellent condition. Ratings of six, seven, and eight indicate the structure is in good condition and does not require any corrective measures. However, a rating of three, four, or five indicates there are problems with the item that need addressed before becoming a critical issue. Corrective measures may include rehabilitation, posting of load limits, or simply increasing the frequency of inspections to track the problem. An item rated with a zero, one, or two it is likely that that particular item, if not the entire bridge, will need to be replaced (Markow & Hyman, 2009).

Table 3: NBIS Condition Ratings, Item 61 (FHWA, 1995)

CODE	DESCRIPTION
N	NOT APPLICABLE, use when bridge is not over a waterway (channel).
9	There are no noticeable or noteworthy deficiencies, which affect the condition of the channel.
8	Banks are protected or well vegetated. River control devices such as spur dikes and embankment protection are not required or are in a stable condition.
7	Bank protection is in need of minor repairs. River control devices and embankment protection have a little minor damage. Banks and/or channel have minor amounts of drift.
6	Bank is beginning to slump. River control devices and embankment protection have widespread minor damage. There is minor streambed movement evident. Debris is restricting

	the channel slightly.
5	Bank protection is being eroded. River control devices and/or embankment have major damage. Trees and brush restrict the channel.
4	Bank and embankment protection is severely undermined. River control devices have severe damage. Large deposits of debris are in the channel.
3	Bank protection has failed. River control devices have been destroyed. Streambed aggradation, degradation or lateral movement has changed the channel to now threaten the bridge and/or approach roadway.
2	The channel has changed to the extent the bridge is near a state of collapse.
1	Bridge closed because of channel failure. Corrective action may put back in light service.
0	Bridge closed because of channel failure. Replacement necessary.

It is essential that inspectors and decision makers understand the goal of the NBIS condition ratings. Therefore, the FHWA *Recording and Coding Guide* provides an explanation of condition ratings that states (FHWA, 1995, p. 37):

> "Condition ratings are used to describe the existing, in-place bridge as compared to the as-built condition. Evaluation is for the materials related, physical condition of the deck, superstructure, and substructure components of a bridge. The condition evaluation of channels and channel protection and culverts is also included. Condition codes are properly used when they provide an overall characterization of the general condition of the entire component being rated. Conversely, they are improperly used if they attempt to describe localized or nominally occurring instances of deterioration or disrepair. Correct assignment of a condition code must, therefore, consider both the severity of the deterioration or disrepair and the extent to which it is widespread throughout the component being rated."

When conducting a condition rating an inspector should evaluate the current condition of the bridge without taking into consideration its age. Taking into account, a bridge's age may affect their assessment of the structural elements. For example, an inspector may conclude that traffic volume and vehicle weights are significantly greater today than the bridge was originally designed and constructed for, and might feel inclined to account for this discrepancy. However, the NBIS clearly states that the condition shall be evaluated independent of load-carrying capacity. Additionally, inspectors should neglect bracing elements when rating an item. In other words, if there is damage to a bridge element and is braced to add structural capacity, the element shall be rated as if the bracing were not there. Finally, the evaluation of items assumed the bridge is open to traffic even if it is closed (FHWA, 1995).

2.2.2 Appraisal Ratings

Appraisal ratings are similar to condition ratings in that they assess the current state of the bridge, however appraisal ratings do take into account current design and safety standards. In other words, the NBIS explicitly states that condition ratings do not account for current design standards differing from past design standards, whereas the appraisal ratings specifically perform that comparison. The NBIS items used for appraisal ratings of a bridge are 67- Structural Evaluation, 68- Deck Geometry, 69 - Under Clearances, Vertical and Horizontal, 71- Waterway Adequacy, and 72- Approach Roadway Alignment. Moreover, the AASHTO CoRe Elements are not applicable to appraisal ratings. Again, it is important that decision makers understand the purpose of appraisal ratings as described by the FHWA *Recording and Coding Guide* (FHWA, 1995, p. 45):

> "The items in the Appraisal Section are used to evaluate a bridge in relation to the level of service which it provides on the highway system of which it is a part. The structure will be compared to a new one which is built to current standards for that particular type of road … except for Item 72 - Approach Roadway Alignment."

Unlike condition ratings, inspectors do not evaluate and coded the appraisal ratings, but rather items 67, 68, 69, and 71 are calculated by the FHWA Edit/Update software program and tables given in the manual (FHWA, 1995). Table 4 provides descriptions of the codes as in the *Recording and Coding Guide*.

Table 4: NBIS Appraisal Ratings (FHWA, 1995)

CODE	DESCRIPTION
N	Not Applicable
9	Superior to present desirable criteria
8	Equal to present desirable criteria

7	Better than present minimum criteria
6	Equal to present minimum criteria
5	Somewhat better than minimum adequacy to tolerate being left in place as is
4	Meets minimum tolerable limits to be left in place as is
3	Basically intolerable requiring high priority of corrective action
2	Basically intolerable requiring high priority of replacement
1	This value of rating code not used
0	Bridge closed

Generally speaking, the older a structure the more deterioration and thus a lower NBIS condition rating. Appraisal ratings do not necessarily follow the same time based logic. For instance significant foresight could have used by planners and designer for a bridge constructed several decades ago and thus the structure still conforms to current standards and may receive a high appraisal rating when examining items 68-Deck Geometry and 69-Under Clearances, which deal with geometrics. As an example if a bridge was constructed with 11 foot wide travel lanes and the current standard is 12 feet, and the minimum vertical clearance over another roadway is 15 feet and the current design standard is 16 feet, then this bridge would receive lower ratings for items 68 and 69 (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008). However, if the numbers in the previous example were reversed than the bridge would receive higher ratings.

Although appraisal ratings take into account the current standards relative to the characteristic of the bridge at the time of construction, item 72 - Approach Roadway Alignment is the exception. For this item, comparison between the approach roadway alignment and the existing bridge alignment ensures they are able to function together in a manner that allows for safe, continuous travel over the bridge (FHWA, 1995).

2.2.3 BRIDGE DEFICIENCIES

Upon completion of the inspection and assessment of a bridge, the inspector assigns the appropriate NBIS condition and appraisal ratings. These coded values inform decision makers, inspectors and other stakeholders of the overall status of the structure. Low code values indicate the bridge has defects and thus designation as either Structurally Deficient or Functionally Obsolete, which are not mutually exclusive. However, a bridge is only reported as Structurally Deficient if it is both Structurally Deficient and Functionally Obsolete. Therefore, bridges belong to one of three statistical categories in the NBI, Structurally Deficient, Functionally Obsolete, or non-deficient (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008).

In general, bridges are classified as Structurally Deficient if its condition ratings are low and Functionally Obsolete if its appraisal ratings are low. However, there are cases in which a structure is categorized as Structurally Deficient by means of an appraisal rating, specifically item 67-Structural Evaluation, which measures load-carrying capacity and item 71 - Waterway Adequacy. For these items, if a bridge receives a rating of three it is considered Functionally Obsolete. On the other hand, if it receives a rating of two or less it is classified as Structurally Deficient. Overall, a rating of three means the factor causing a lack of capacity can be mitigated and a rating of two or less means the structure will need replaced (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008). Section 2.2.3.1 expands upon this topic.

Normally a Structurally Deficient rating is considered more critical than Functionally Obsolete" because they have the potential to eventually lead to a loss of functionality or even closure unless the bridge is rehabilitated or replaced" (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008, pp. 3-17). There is a good possibility that a Structurally Deficient bridge is Functionally Obsolete as well. Whereas a bridge that is

Functionally Obsolete may not have structural defects, but rather is simply not up to current design standards and practices (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008). The most recent numbers for Structurally Deficient and Functionally Obsolete bridges from the NBI are from 2009 and are presented in Table 5. Again, note that if a bridge is both Structurally Deficient and Functionally Obsolete, it is only listed as Structurally Deficient.

Table 5: NBI Statistics on Bridge Deficiency, as of 12/31/2010 (FHWA, 2010)

State	Number of Bridges	Number of SD Bridges	Number of FO Bridges	Total SD or FO Bridges	% of SD or FO Bridges
Alabama	16,018	1,592	2,084	3,676	22.9%
Alaska	1,134	138	142	280	24.7%
Arizona	7,578	230	673	903	11.9%
Arkansas	12,587	930	1,884	2,814	22.4%
California	24,557	3,135	3,956	7,091	28.9%
Colorado	8,506	578	821	1,399	16.4%
Connecticut	4,191	383	1,028	1,411	33.7%
Delaware	861	50	111	161	18.7%
District of Columbia	244	30	128	158	64.8%
Florida	11,912	290	1,593	1,883	15.8%
Georgia	14,670	941	1,788	2,729	18.6%
Hawaii	1,137	141	366	507	44.6%
Idaho	4,132	373	414	787	19.0%
Illinois	26,337	2,239	1,763	4,002	15.2%
Indiana	18,548	1,975	2,028	4,003	21.6%
Iowa	24,731	5,372	1,227	6,599	26.7%
Kansas	25,329	2,816	2,083	4,899	19.3%
Kentucky	13,849	1,311	3,000	4,311	31.1%
Louisiana	13,361	1,722	2,107	3,829	28.7%
Maine	2,393	369	402	771	32.2%
Maryland	5,195	364	958	1,322	25.4%
Massachusetts	5,113	558	1,990	2,548	49.8%
Michigan	10,928	1,437	1,289	2,726	24.9%
Minnesota	13,108	1,149	388	1,537	11.7%
Mississippi	17,065	2,650	1,369	4,019	23.6%
Missouri	24,245	4,075	2,946	7,021	29.0%
Montana	5,119	391	486	877	17.1%
Nebraska	15,376	2,797	997	3,794	24.7%
Nevada	1,753	39	169	208	11.9%
New Hampshire	2,409	371	376	747	31.0%

New Jersey	6,520	674	1,606	2,280	35.0%
New Mexico	3,903	330	312	642	16.4%
New York	17,365	2,088	4,379	6,467	37.2%
North Carolina	18,099	2,353	2,623	4,976	27.5%
North Dakota	4,418	710	233	943	21.3%
Ohio	28,033	2,742	3,856	6,598	23.5%
Oklahoma	23,692	5,212	1,599	6,811	28.7%
Oregon	7,255	456	1,194	1,650	22.7%
Pennsylvania	22,359	5,906	3,702	9,608	43.0%
Rhode Island	757	163	233	396	52.3%
South Carolina	9,252	1,210	785	1,995	21.6%
South Dakota	5,891	1,193	232	1,425	24.2%
Tennessee	19,892	1,225	2,631	3,856	19.4%
Texas	51,440	1,618	7,515	9,133	17.8%
Utah	2,911	130	290	420	14.4%
Vermont	2,712	326	535	861	31.7%
Virginia	13,522	1,267	2,162	3,429	25.4%
Washington	7,755	394	1,577	1,971	25.4%
West Virginia	7,069	1,018	1,525	2,543	36.0%
Wisconsin	13,982	1,142	719	1,861	13.3%
Wyoming	3,060	395	266	661	21.6%
Puerto Rico	2,201	225	870	1,095	49.8%
Totals	**604,474**	**69,223**	**77,410**	**146,633**	**24.3%**

The previously discussed method for classifying bridges as Structurally Deficient or Functionally Obsolete has some negative implications. First, the NBI data shown in Table 5 does not delineate whether only one or several items were rated poor, nor does it provide information as to which item(s) was (were) rate (d) poor. Secondly, the overall structural integrity of the bridge may not be reflected. Hence, this simplistic evaluation indicates bridge deficiencies that require further attention, but it does not convey the details of the problem (Markow & Hyman, 2009).

2.2.3.1 STRUCTURAL DEFICIENCY

A bridge is Structurally Deficient if one of the condition ratings of items 58, 59, 60 or 62 has a value of four or less, or if one of the appraisal ratings of items 67 or 71 has a value of two or less as seen in Table 6 (FHWA). Item 61 – Channel and Channel Protection is not included by the *Non-Regulatory Supplement 23CFR650 Subpart D*in categorizing bridges as Structurally Deficient. The criteria presented in Table 6 are "poor or worse" for condition ratings as defined in Table 2 and "intolerable with a high priority of replacement" for appraisal ratings per Table 4.

Table 6: Criteria for Structural Deficiency Classification (FHWA)

NBIS Rating Item	Item Description	Type of Rating	Criterion
58	Deck	Condition	≤ 4
59	Superstructure	Condition	≤ 4
60	Substructure	Condition	≤ 4
62	Culvert	Condition	≤ 4
67	Structural Evaluation	Appraisal	≤ 2
71	Waterway Adequacy	Appraisal	≤ 2

There is a lack of understanding of what it means when a bridge is classified as Structurally Deficient or Functionally Obsolete and how that relates to the safety of the traveling public. The 2008 *Conditions and Performance report to Congress* clarifies this issue by stating (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008, pp. 3-13):

> "Structurally Deficient bridges are not inherently unsafe. Bridges are considered Structurally Deficient if significant load-carrying elements are found to be in poor or worse condition due to deterioration and/or damage, or the adequacy of the waterway opening provided by the bridge is determined to be extremely insufficient to the point of causing intolerable traffic interruptions. That a bridge is deficient does not imply that it is likely to collapse or that it is unsafe. By conducting properly scheduled inspections, unsafe conditions may be identified; if the bridge is determined to be unsafe, the structure must be closed. A deficient bridge, when left open to traffic, typically requires significant maintenance and repair to remain in service and eventual rehabilitation or replacement to address deficiencies. To remain in service, Structurally Deficient bridges often have weight limits that restrict the gross weight of vehicles using the bridges to less than the maximum weight typically allowed by statute."

Although both condition and appraisal ratings may result in a bridge being classified as Structurally Deficient, the primary reason is a low condition rating. The FHWA found that 80% of Structurally Deficient bridges are due to a low condition rating (Markow & Hyman, 2009). In addition, around 50% of Structurally Deficient bridges will have issues related to functional obsolescence as well (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008).

2.2.3.2 FUNCTIONAL OBSOLESCENCE

A bridge is Functionally Obsolete if one of the appraisal ratings of items 68, 69, or 72 has a value of three or less, or if item 67 or 71 have a value of three as seen in Table 7 (FHWA).

Table 7: Criteria for Functional Obsolescence Classification (FHWA)

NBIS Rating Item	Item Description	Criterion
67	Structural Evaluation	= 3
68	Deck Geometry	≤ 3
69	Under Clearances , Vertical and Horizontal	≤ 3
71	Waterway Adequacy	= 3
72	Approach Roadway Alignment	≤ 3

Items 67 and 71 are used to determine if the structure is either Structurally Deficient or Functionally Obsolete. If their rating is three it is considered Functionally Obsolete; a rating of two or less it is classified as Structurally Deficient. The FHWA explains why a bridge becomes Functionally Obsolete in the following way (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008, pp. 3-13):

> "Functional obsolescence is a function of the geometrics (i.e., lane width, number of lanes on the bridge, shoulder width, presence of guardrails on the approaches, etc.) of the bridge in relation to the geometrics required by current design standards. While structural deficiencies are generally the result of deterioration of the conditions of the bridge components, functional obsolescence generally results from changing traffic demands on the structure. Facilities, including bridges, are designed to conform to the design standards in place at the time they are designed. Over time, improvements are made to the design requirements."

2.2.4 SUFFICIENCY RATING

The Sufficiency Rating is found in Appendix B of the FHWA *Recording and Coding Guide* and is defined as "a method of evaluating highway bridge data by calculating four separate factors to obtain a numeric value which is indicative of bridge sufficiency to remain in service" (FHWA, 1995, pp. B-1).

Sufficiency Ratings start out with a value of 100 (highest value corresponding to 100 percent sufficient) then deductions are taken for bridge deficiencies, down to a potential value of zero (lowest value relating to zero percent sufficient). Figure 6 illustrates the four rating components. These components are comprised of, Structural Adequacy and Safety – S_1 that has a value of 55, Serviceability and Functional Obsolescence - S_2that accounts for a value of 30, Essentiality for Public Use - S_3 that receives a value of 15, and finally Special Reductions - S_4 with a value of 13. It should be noted that Special Reductions - S_4 are just that, they strictly reduce the Sufficiency Rating and is only applicable when the sum of the other three components are greater than 50, otherwise the value is taken as zero.

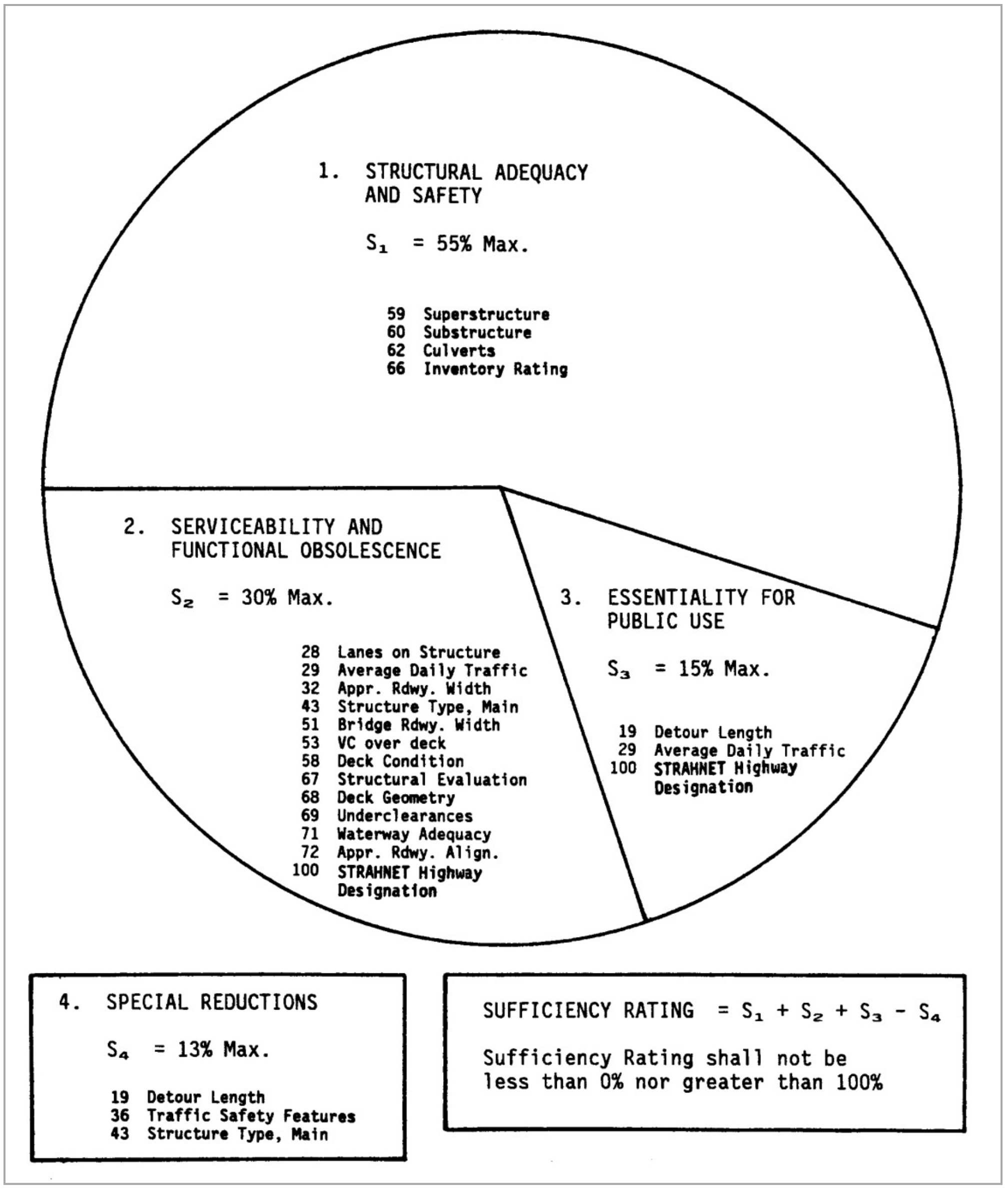

Figure 6: Diagram of Sufficiency Rating Factors (FHWA, 1995)

In addition to Figure 6, a bulleted list of the individual items that make up each component of the Sufficiency Rating is provided below for clarity (FHWA, 1995):

- Structural Adequacy and Safety - S_1
  - Item 59, Superstructure
  - Item 60, Substructure
  - Item 62, Culverts
  - Item 66, Inventory rating

- Serviceability and Functional Obsolescence - S_2
    - Item 28, Number of lanes on and under the structure
    - Item 29, Average daily traffic (ADT)
    - Item 32, Approach roadway width
    - Item 43, Structure type, main
    - Item 51, Bridge roadway width, curb-to curb
    - Item 53, Vertical clearance over bridge roadway
    - Item 58, Deck
    - Item 67, Structural evaluation
    - Item 68, Deck geometry
    - Item 69, Underclearance, vertical and horizontal
    - Item 71, Waterway adequacy
    - Item 72, Approach roadway alignment
    - Item 100, STRAHNET Highway designation
- Essentiality for Public Use - S_3
    - Item 19, Detour length
    - Item 29, ADT
    - Item 100, STRAHNET Highway designation
- Special Reductions - S_4
    - Item 19, Detour length
    - Item 36, Traffic safety features
    - Item 43, Structure type, main

It should be noted that the items used to determine if a bridge is Structurally Deficient or Functionally Obsolete are different than the respective items utilized by Structural Adequacy and Safety - S_1 and Serviceability and Functional Obsolescence - S_2 (Markow & Hyman, 2009). This is important because while the NBI database contains information about the number of bridges that are either Structurally Deficient or Functionally Obsolete, it does not provide information on bridges' Sufficiency Ratings. When discussing deficiencies of structures on the NHS most literature, including the FHWA – FTA biennial *Condition and Performance report to Congress*, primarily allude to, and make use of the NBI and only briefly talk about Sufficiency Ratings. Therefore, the Sufficiency Ratings for bridges are often only known and used by a transportation agency for funding and management of bridges on their network. The reader is referred to Section 1.4 for information on how the Sufficiency Rating influences funding decisions.

Given the previous discussion it is imperative to distinguish what individual items are utilized by a particular bridge rating methodology (i.e. Sufficiency Rating or BHI), along with their relative importance, which is the basis for this research. To help fully understand how a Sufficiency Rating is calculated, an explanation of the methodology is provided and followed by example calculations for a hypothetical bridge.

2.2.4.1 SUFFICIENCY RATING – METHODOLOGY

Structural Adequacy and Safety $S_1 = 55 - (A + B)$: Scoring starts by taking the lowest rating of items 59, 60 and 62 to determine the value "A". Note that items 59 and 60 are for bridges and item 62 is for culverts. A condition rating of five is a reduction of 10%, a rating of four is a reduction 25%, and a rating of three is a reduction of 40% and a rating of two or less is a reduction of 50%. Next is a reduction factor for the inventory rating (value "B"). The inventory rating (IR) is a ratio of how much live load a structure can theoretically resist given by the following equation, $IR = \frac{Capacity - Dead\ Load}{Live\ Load}$. To get the live load IR in terms of tons the equation reduces to $IR = Capacity - Dead\ Load$. The equation for reduction factor "B" is given by the equation $B = [(32.4 - IR)^{1.5} \times 0.3254]$ and cannot be less than zero.

Serviceability and Functional Obsolescence $S_2 = 30 - [J + (G + H) + I]$: This section begins by taking reductions based on several condition and appraisal ratings. The equation for reduction factor "J" is $J = (A + B + C + D + E + F)$, where A, B, C, D, E and F correspond to the NBIS items 58, 67, 68, 69, 71 and 72 respectively. The maximum reduction is 13%. For each item a rating of five is equivalent to a reduction of 1%, a rating of four is a reduction of 2% and a rating of three or less is a reduction of 4%; except item 58 where a rating of four is a reduction of 3% and a rating of three or less is a reduction of 5%. Next, reductions "G" and "H" deal with the adequacy of the roadway width, specifically NBIS items 28, 29, 32, 43 and 51. Two ratios are calculated "X" and "Y", where $X = \frac{Item\ 29\ (ADT)}{Item\ 28\ (Lanes)}$ and $Y = \frac{Item\ 51\ (Bridge\ Roadway\ Width)}{Item\ 28\ (Lanes)}$, after which a set of criteria used to determine the reductions. First, the reduction value of "G" is 5% if Item 51 (in meters) plus 0.6 meters is less than Item 32 approach roadway width (in meters), if not then no reduction is taken. It should be noted this is only relevant if the structure type (Item 43) is not a culvert. The next criterion is only valid for single lane bridges and is an if-then-else relationship with ratio "Y". The third criteria is a limit check of the ratio "Y", based on the number of lanes (Item 28), and if any of the limits are applicable the reduction value "H" is equal to 0% and the final criteria need not be checked. The final criteria is used when the limits for the third criteria are not valid and entails comparing the values for "X" and "Y" to several numeric ranges to obtain the reduction value "H". Finally the reduction value "I" utilizes NBIS Items 53 and 100. If Item 100 is coded greater than zero, then the minimum vertical clearance (Item 53) needs to be 4.87 meters, otherwise the minimum vertical clearance needs to be 4.26 meters. Reduction factor "I" is 2% if the vertical clearance is not met.

Essentiality for Public Use $S_3 = 15 - (A + B)$: Evaluations in this section integrate the final scores for the previous two sections (S_1 and S_2). The equation for reduction value "A" is $A = \frac{Item\ 29\ (ADT) \times Item\ 19\ (Detour\ Length)}{320{,}000 \times K}$ where $K = \frac{S_1 + S_2}{85}$, and has a maximum value of 15%. Reduction factor "B" is 2%, if the code for item 100 is greater than zero and 0% if Item 100's code is equal to zero.

Special Reductions $S_4 = A + B + C$: Special reductions are only taken if the sum of the previous three scores (S_1, S_2 and S_3) is greater than or equal to 50. Reduction value "A" is given by the equation $A = [Item\ 19\ x\ (7.9\ x\ 10^{-9})]$ and must be greater than 0% and less than 5%. The reduction value "B" is equal to 5% if the second and third digits in the code for Item 43 are equal to 10, 12, 13, 14, 15, 16 or 17. Finally, if two, three, or four of the digits coded for Traffic Safety Features (item 36) are coded as zero, then the reduction value "C" is 1%, 2%, or 3% respectively. The maximum reduction for S_4 is 13%.

2.2.4.2 Sufficiency Rating – Example Calculations

The following example calculations are adapted from Appendix B of the FHWA *Recording and Coding Guide* (FHWA, 1995).

Structural Adequacy and Safety - S_1

$$\textit{Items 59 and 60 ratings are } 4 \therefore A = 25\%$$

$$IR = 28.5 \text{ tons} \therefore B = [(32.4 - 28.5)^{1.5} \times 0.3254] = 2.5\%$$

$$S_1 = 55\% - (25\% + 2.5\%) = \underline{\underline{27.5\%}}$$

Serviceability and Functinal Obsolescence - S_2

$$\textit{Item 58 rating is } 4 \therefore A = 3\%$$

$$\textit{Items 68,71 and 72 ratings are } 5 \therefore C, E \text{ and } F = 1\%$$

$$\textit{Items 67 and 69 ratings are } 3 \therefore B \text{ and } D = 4\%$$

$$J = 3\% + 4\% + 1\% + 4\% + 1\% + 1\% = 14\%, \text{ but Max is } 13\% \therefore J = 13\%$$

Item 29 = 10650 and the bridge is two lanes (Item 28 = 0200),

with a width of 34 feet (Item 51 = 0105) and approach roadway width of 38 feet (Item 32 = 0117)

$$X = \frac{10650}{2} = 5325 \text{ and } Y = \frac{10.5}{2} = 5.25$$

$$\text{If } (5.25 + 0.6) < 11.7 \text{ then } G = 5\% \Rightarrow 5.85 < 11.7 \therefore G = 5\%$$

Serviceability and Functinal Obsolescence - S_2 (continued)

$If\ \ first\ two\ digits\ of\ \ Item\ 28 = 02\ and\ Y \geq 4.9\ then\ H = 0\%$

$Y = 5.25 > 4.9 \therefore H = 0\%$

$G + H = 5\% + 0\% = 5\%$

$Item\ 100 = 1\ and\ Item\ 53 = 16\ \ feet\ (4.92\ meters) \therefore I = 0\%$

$S_2 = 30\% - \left[13\% + (5\%) + 0\%\right] = \underline{\underline{12\%}}$

Essentiality for Public Use - S_3

$$K = \frac{S_1 + S_2}{85} \Rightarrow \frac{27.5\% + 12\%}{85} = 0.465$$

$Detour\ Length = 15\ miles = 9.23\ kM$

$$A = 15\left(\frac{10650 \times 9.23}{320{,}000 \times 0.465}\right) = 9.91\%$$

$Item100 = 1 \therefore B = 2\%$

$S_3 = 15\% - \left(9.9\% + 2\%\right) = \underline{\underline{3.1\%}}$

Special Reductions - S_4 (when $S_1 + S_2 + S_3 \leq 50$)

$S_1 + S_2 + S_3 = 27.5\% + 12\% + 3.1\% = \underline{\underline{42.6\%}}$

$42.6\% < 50\% \therefore S_4 = N.A.$

Sufficiency Rating $= 27.5\% + 12\% + 3.1\% = 42.6\%$

As can be seen from the previous calculations and as alluded to in Section 1.4, factors such as a long detour and high ADT can cause potential bridge management issues. Markow and Hyman state "if a bridge has an attribute that causes a Special Reduction – for example, a long detour route – its [Sufficiency Rating] SR can never be a the theoretical maximum – that is, [Sufficiency Rating] SR < 100 even when the bridge is new" (Markow & Hyman, 2009, p. 15).

2.3 BRIDGE MANAGEMENT

Recently, *NCHRP Synthesis 397* investigated the state of bridge management, and how transportation agencies use BMSs to make decisions. The report depicts the vital role bridges have on a transportation system and the importance of thorough asset management. The authors note that maintenance, rehabilitation and replacement of bridges is very costly and thus prudent financial decisions to improve the structural condition and/or the serviceability of a bridge is of the utmost importance; not only to account for available funds but to ensure a safe and effective transportation system (Markow & Hyman, 2009). Deciding on the most beneficial allocation of resources is a difficult task for decision makers in a transportation agency. The following sections discuss current bridge management strategies and BMSs utilized by transportation agencies to aid in decision-making.

2.3.1 NATIONAL BRIDGE INVESTMENT ANALYSIS SYSTEM (NBIAS)

Every other year the FHWA and FTA publishes the *Conditions and Performance Report to Congress*, which includes comprehensive information about bridges on the NHS with details of past performance and projections about future operation which are based on funding and various management strategies. The FHWA accomplishes this by means of a forecasting model called the National Bridge Investment Analysis System (NBIAS) (Markow & Hyman, 2009). The NBIAS is defined as "an investment analysis tool used to analyze bridge repair, rehabilitation and functional improvement investment needs" (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008, pp. B-2) and is a decision aid for transportation funding and policy makers in the United States Congress (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008).

Development of the NBIAS began in the mid-1990s and encompassed very similar analytical methods as the Pontis BMS. The first introduction of the NBIAS occurred in the 1999 edition of the *Conditions and Performance Report to Congress*. In addition to examining the increase in bridge needs, NBIAS has the capability to review the distribution of bridges based on a benefit-cost ratio for work completed along with revealing current bridge conditions based on physical measures. Analysis results may be organized and viewed in a variety of ways. Condition states, deterioration curves, and recommended actions generated by NBIAS are experience-based and congruent with predictive models created by Pontis. NBIAS differs from Pontis in that it has the ability to synthesize CoRe element data from the NBI data reported by States as well as employing element data directly. The program is able to deduce what elements, including their condition, are present on a bridge by means of Synthesis, Quantity and Condition (SQC) models. Moreover, NBIAS features economic forecasting tools to assist policy makers estimate funding necessary to meet their performance measures over a specified time (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008). The reader is referred to the following section on performance and funding measures (Section 2.3.1.1) for further information.

Similar to the NBIS classification of Structurally Deficient, NBIAS determines improvement and preservation needs. As previously stated NBAIS first determines what elements make up the bridge through SQC models, then uses probability and modeling techniques similar to those in Pontis to establish the deterioration of bridge elements over an established period. Upon developing deterioration curves, the program resolves optimal repair and rehabilitation measures for each bridge element using Markov modeling. Although analysis is typically done at the National level to generate the *Conditions and Performance Report to Congress*, the NBIAS can conduct analyses at the individual bridge level and evaluate costs and benefits for rehabilitation and replacement work (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008).

In addition to repair, rehabilitation and replacement the NBIAS identifies needs for serviceability improvements, which is similar to the NBIS classification Functionally Obsolete.

The program reviews bridge characteristics and compares them to current design standards, “then identifies potential improvements—such as widening existing bridge lanes, raising bridges to increase vertical clearances, and strengthening bridges to increase load-carrying capacity—and evaluates their potential benefits and costs” (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008, pp. 7-4). It should be noted that for functional improvements the benefits are proportionate to the average daily traffic (ADT). Hence, the higher the ADT the more likely the bridge will have a favorable benefit-cost ratio for functional improvements (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008).For example, if a bridge has substandard design and safety features, but is in a rural area with an extremely low ADT, then the benefit-cost ratio may not justify the capital expenditure to improve the bridge. Whereas a bridge in an urban area would have a large ADT and could greatly benefit from having a single design or safety standard improved.

2.3.1.1 PERFORMANCE AND FUNDING MEASURES

While the NBIAS is an effective assessment tool, policy and decision makers still require a technique for making bridge management decisions. In the *2008 Conditions and Performance Report to Congress*, Chapter 11 specifically examines several bridge management strategies and funding alternatives to illustrate potential decision-making processes. The reader should be aware that while the NBIAS may be an effective BMS, it is primarily used for generating reports for the United States Congress to reference when developing budgets and writing funding legislation. The report defines the bridge management strategies as follows (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008, pp. 11-5):

- No Special Rules Strategy: Applies the default NBIAS criteria in which bridge actions are only implemented when their estimated benefit-cost ratio is 1.0 or higher based on the funding alternative being considered.

- SR 50 Strategy: Bridges with a Sufficiency Rating of 50 or less are selected for replacement in addition to any actions that have a minimum 1.0 benefit-cost ratio, in order of benefit-cost ratio and are based on the funding alternative being considered.
- Age 50 Strategy: Assumes any structure that becomes 50 years in age or older during the analysis period will be replaced in addition to any actions that have a minimum 1.0 benefit-cost ratio, in order of benefit-cost ratio and is based on the funding alternative being considered.
- 75, 80 and 85 Health Index Strategy: Assumes any structure with a respective health index equal to or less than 75, 80 or 85 during the analysis period will be replaced in addition to any actions that have a minimum 1.0 benefit-cost ratio, in order of benefit-cost ratio and are based on the funding alternative being considered.

The report defines the funding alternatives as follows (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008, pp. 11-6):

- Current Funding (CF) Alternative: Assumes the expenditure of funds will be sustained in constant dollar terms, for the duration of a50 year analysis period.
- Maximum Ramped Funding (MRF) Alternative: Assumes an increase in spending at a fixed annual rate above the base year for the 50-year period. For each management strategy to which this alternative is applied, the rate of increase is determined as the maximum rate for which NBIAS can identify a sufficient number of potential projects meeting the specified criteria, for that strategy, in each individual year, to allow the funding available in each year to be fully expended.
- The Maximum Flat Funding (MFF) Alternative: Assumes an immediate increase in spending to a higher level that would be maintained in constant dollar terms for the entire 50-year period. For each management strategy to which this alternative is applied, the investment level is determined as the maximum level for which NBIAS can identify a

sufficient number of potential projects meeting the specified criteria, for that strategy, in each individual year, to allow the funding available in each year to be fully expended.

- The Unconstrained Funding (UF) Alternative: Assumes that spending in each year will be based solely on the criteria of the management strategy being analyzed. This approach would front-load spending in the first year of the analysis to address the existing backlog of bridge deficiencies.

The various funding alternatives were combined with the bridge management strategies to illustrate funding implications for policy makers in Congress. Following is an overview of the analysis.

The SR 50 Strategy showed a decline in the selected measures at some point in the analysis period regardless of which funding alternative was applied. Table 8 and Figure 7 illustrate the performance projections and increase in funding for the MRF respectively.

Table 8: Performance Projection – SR 50 Strategy with MRF Alternative (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008)

Measure	Year					
	2006	2016	2026	2036	2046	2056
Sufficiency Rating	82.8	76.5	71.4	73	75.4	78.3
Health Index	92.0	82.2	77.3	75.7	77.3	80.3
% of Bridges with Deck Rating of 5 or greater	95.4	96.1	94.8	92.3	94.3	98.4
% of Bridges with Superstructure Rating of 5 or greater	97.9	95.7	89.6	86.4	88.9	94.2
% of Bridges with Substructure Rating of 5 or greater	98.1	88.1	57.1	61.6	67.8	77.3

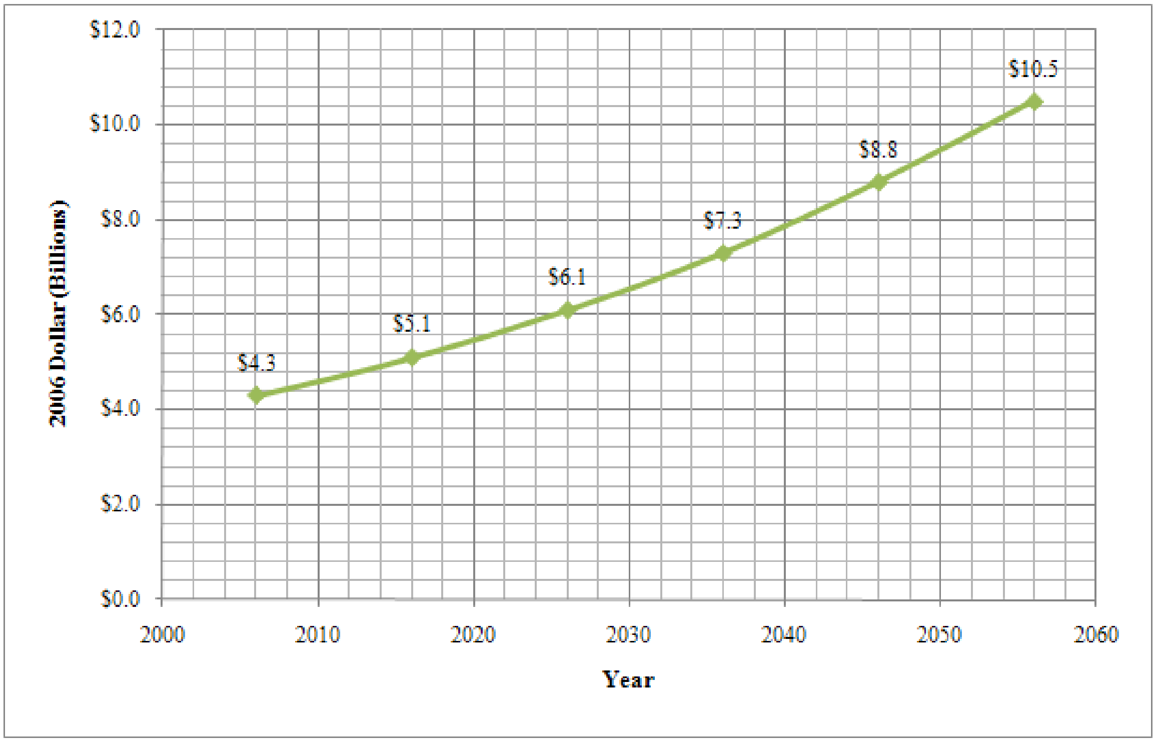

Figure 7: Annual Funding Level – SR 50 Strategy with MRF Alternative (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008)

Overall, the Health Index Strategies (75, 80, and 85) performed in a very similar fashion with regards performance projections. However, as the target health index is increased the funding levels required to maintain that target increased as well. The MRF and MFF for all health index strategies and their heath index performance projection are illustrated in Figures 8 and 9.

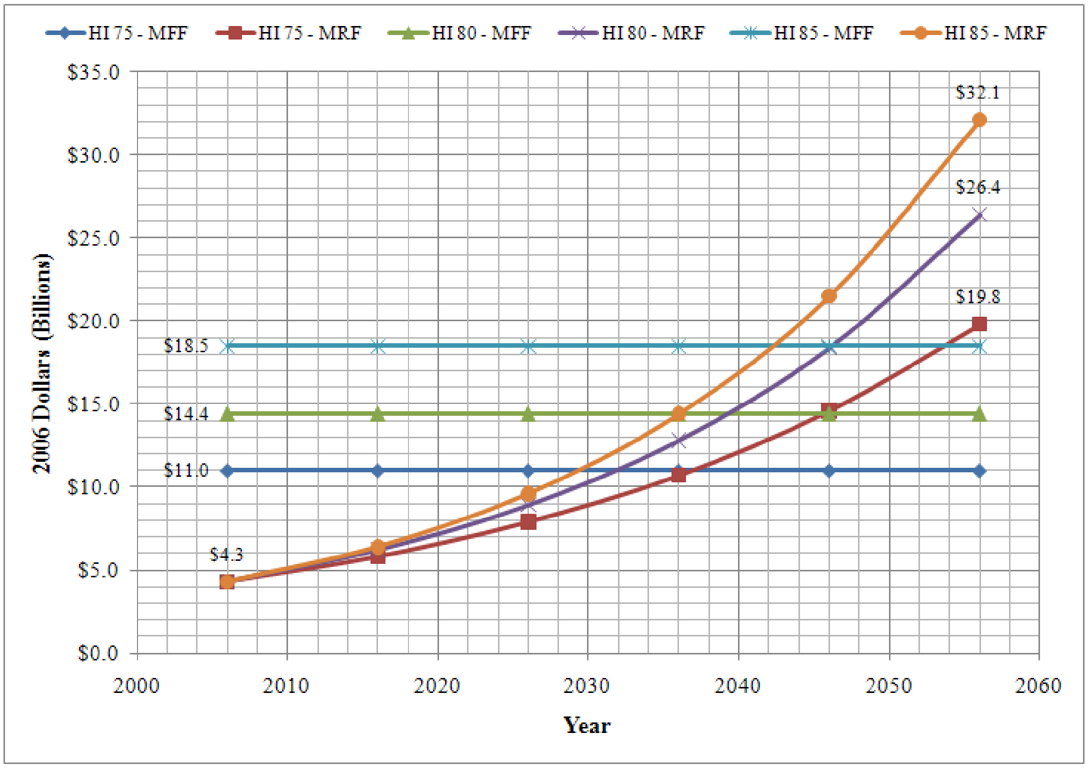

Figure 8: Annual Funding Level – Health Index Strategies 75, 80 and 85 (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008)

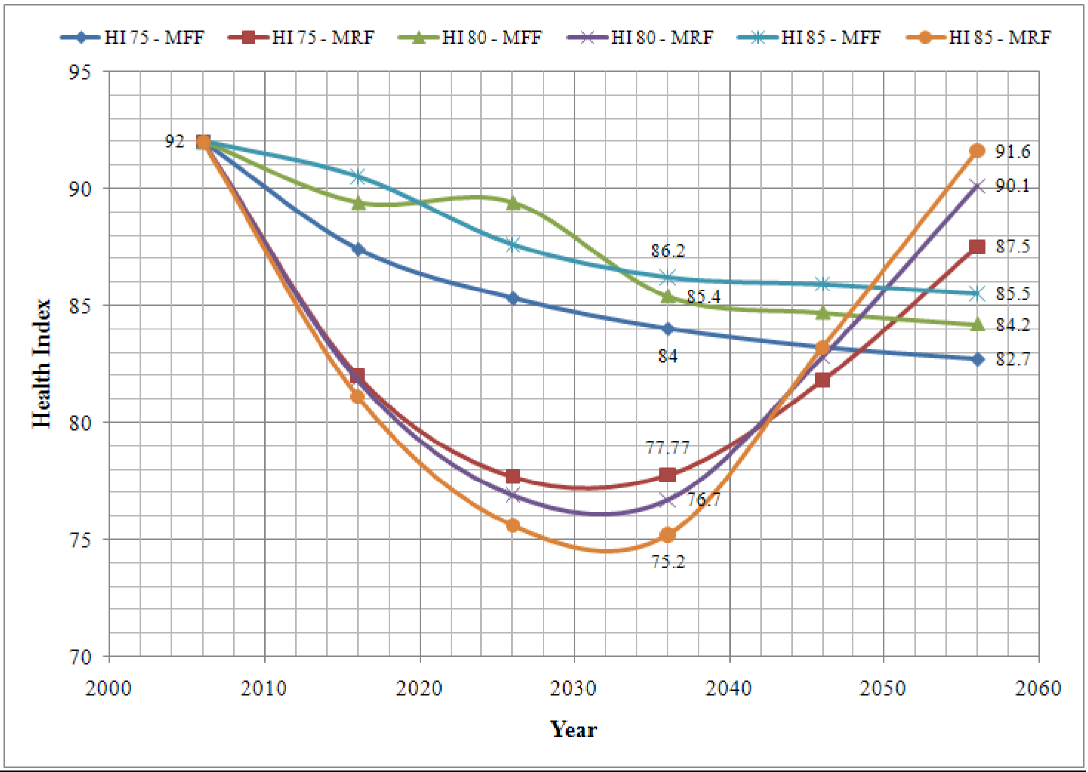

Figure 9: Performance Projections – Health Index Strategies 75, 80 and 85 (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008)

The unconstrained funding alternative was combined with the Age 50 Strategy and the No Special Rules Strategy. This option produced a large spike in funding for the second year as seen in Figure 10. This spike occurs because of the present backlog of bridgework. In addition, Table 9 provides a summary of all scenarios with their lowest condition rating, Sufficiency Rating, and health index at any time in the 50-year analysis period along with the total funds allocated over that same time.

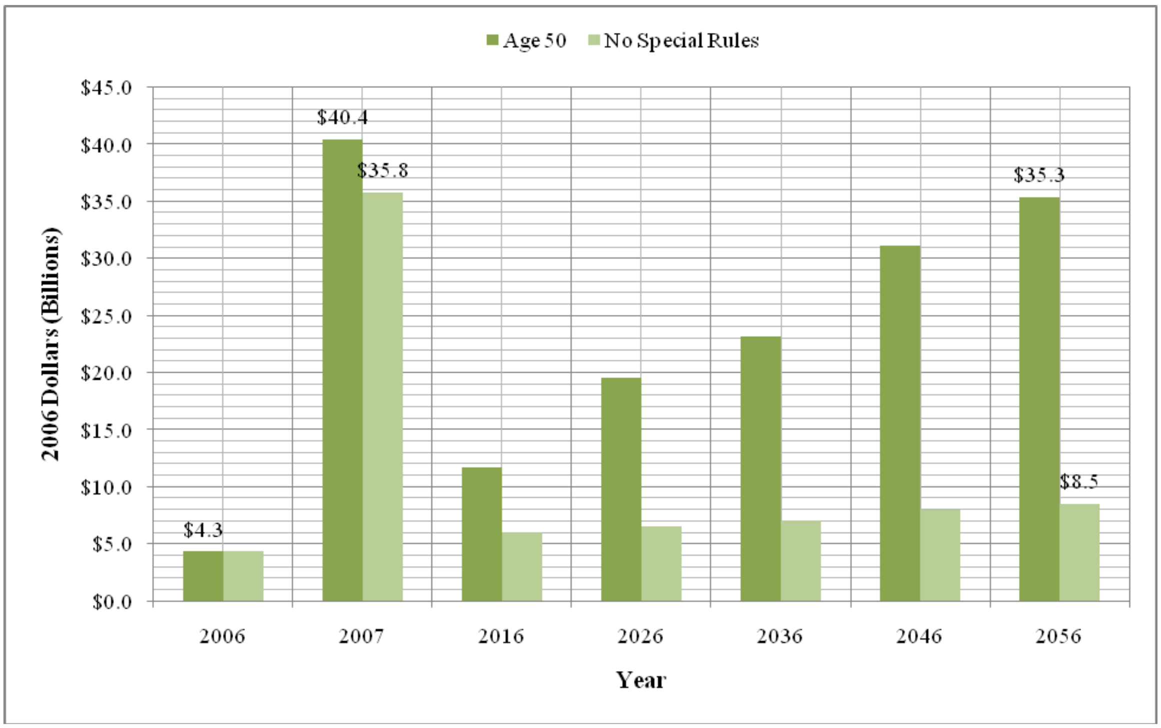

Figure 10: Unconstrained Funding – Age 50 and No Special Rules (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008)

Table 9: Summary of Minimum Performance Projection and Total Funds (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008)

Scenario	% of Deck Ratings ≥ 5	% of Superstructure Ratings ≥ 5	% of Substructure Ratings ≥ 5	Sufficiency Rating	Health Index	Total Allocation (Billions)
SR 50 – Current Funding	84.5	72.4	48.9	67.1	66.8	$215.0
SR 50 – MFF	95.4	92.9	73.7	76.5	78.9	$375.0
SR 50 – MRF	92.3	86.4	57.1	71.4	75.7	$349.7
HI 75 – MFF	95.4	97.7	89.1	79.2	82.7	$550.0
HI 75 – MRF	95.4	90.3	57.7	71.3	77.7	$515.1
HI 80 – MFF	95.4	96.6	88.0	80.4	84.2	$720.0
HI 80 – MRF	93.8	87.7	48.5	70.1	76.7	$620.8
HI 85 – MFF	95.4	95.0	83.8	80.9	85.5	$925.0
HI 85 – MRF	91.5	83.1	42.5	68.6	75.2	$704.9
Age 50 – MFF	93.8	82.4	46.9	70.2	73.7	$565.0
Age 50 – MRF	95.4	88.9	59.7	72.6	78.7	$802.1
Age 50 – Unconstrained	95.4	96.8	88.2	80.6	85.6	$1126.8
No Rules - Unconstrained	95.4	96.9	76.9	75.5	79.2	$359.5

Analyzing potential alternatives using the NBIAS is normally done for the entire NHS in order to point out funding implications for policy makers, by means of the *Conditions and Performance Report to Congress*. Understanding the resources required to implement any alternative is critical. As presented in this section, there are several criteria that decision makers ought to consider when identifying and selecting bridge projects. They accomplish this through the implementation of BMSs and in doing so are able to complete the difficult task of optimizing the use of available resources to maintain a safe and effective network of bridges.

2.3.2 PONTIS

Presently, the most well know BMS, which is licensed to several State DOTs and other organizations, is the Pontis BMS. As illustrated earlier in Figure 5, some agencies use all of the features available in Pontis while others simply use the program for inspection and inventory data management. Pontis is a program originally developed by the FHWA, but is now owned administrated, and maintained by AASHTO. Pontis is a wide-ranging BMS that assists agencies in optimizing their use of available resources for inspection, and establishing maintenance and improvement needs of bridges, to ensure a safe and effective transportation system. The program includes four major bridge management functions organized into seven modules, as presented in *Pontis Release 4.5 and 5.1 User's Manual* (Michael Baker Jr., Inc.; Cambridge Systematics, Inc., 2009, pp. 1-3 and 1-4):

<u>Major Functions</u>

- Bridge Inventory
  - Establishing an accurate inventory of structure information
  - Integration and data exchange with existing enterprise information systems
- Bridge Inspections
  - Scheduling and conducting structure inspections
  - Entering inspection data
  - Importing data from external inspection data collection systems
  - Producing required NBI files
  - Producing structure, inventory, appraisal and other inspection reports
- Needs Assessment and Strategy Development
  - Developing structure deterioration and cost models based on agency historical data and experience
  - Developing long-range, network-wide policies for structure preservation and improvement reflecting economic considerations and agency standards
  - Assessing current and future maintenance and replacement needs
  - Evaluating alternative investment scenarios, based on structure condition and performance, and benefit/cost considerations

- Project and Program Development
    - o Developing projects to address inspector work recommendations and agency policies and standards
    - o Evaluating impacts of project alternatives on structure performance
    - o Project ranking
    - o Developing budget-constrained programs of projects
    - o Tracking project status and completion

Figure 11shows a general overview of how Pontis incorporates the aforementioned major functions.

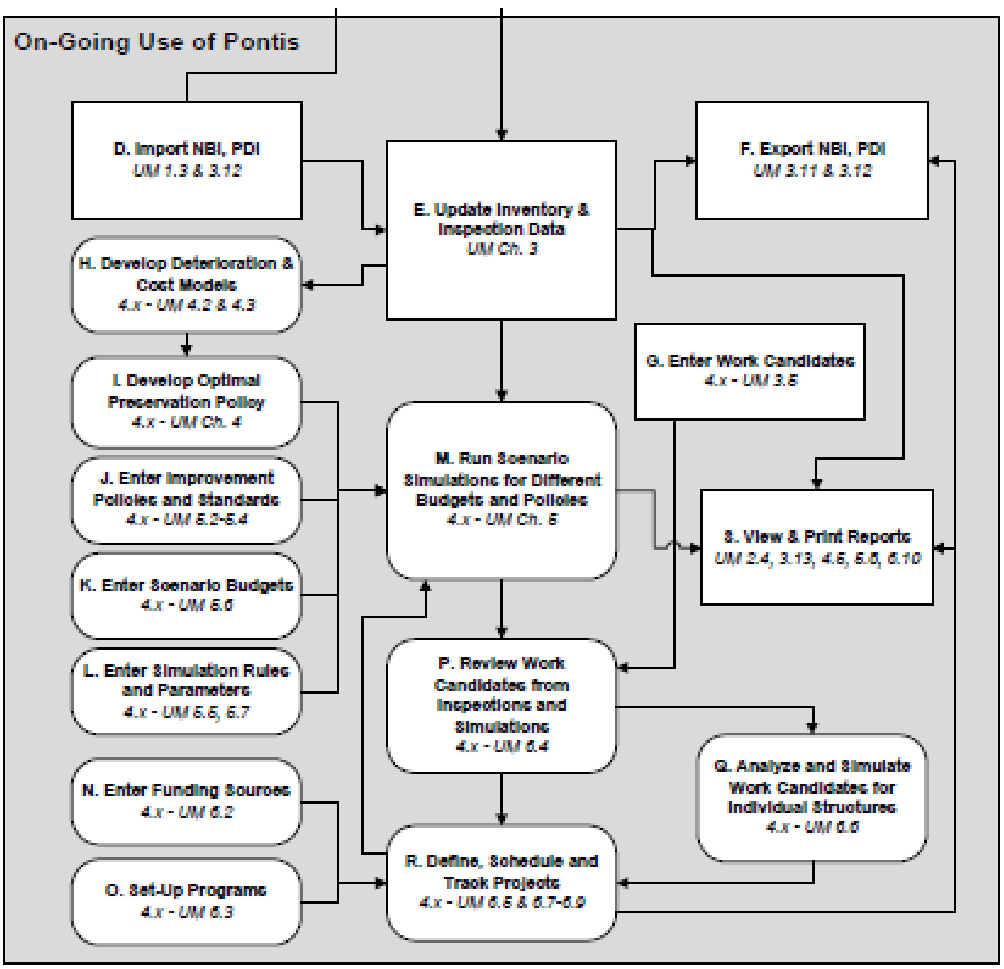

Figure 11: Pontis Work Flow Overview (Michael Baker Jr., Inc.; Cambridge Systematics, Inc., 2009, pp. 1-7)

Modules

- Inspection Module: Used to maintain inventory and inspection information about structures.
- Preservation Module: Develop and run models for determining the optimal long-term preservation policy that minimizes life cycle costs while keeping elements out of risk of failure.
- Programming Module: Set up structure improvement policies and standards, and to define and run simulations of alternative multi-year, budget-constrained program scenarios.
- Project Planning Module: Provides a flexible set of tools to assist with project development. It allows viewing the needs for each structure, and analyzes future structure performance for different assumptions about what work will be done. Helps schedule projects for individual structures, define budget-constrained programs of structure projects, and record information about projects that have been completed.
- Results Module: View graphical reports on the predicted network costs and performance associated with different scenarios and programs of projects.
- Gateway Module: Used to import and export data between Pontis and other systems.
- Configuration Module: Used to customize Pontis according to the needs of individual agencies.

Figure 12 shows the analytical bridge management process of the modules in Pontis, which is discussed further in section 2.3.2.2 Analytical Procedure and Modeling Approach.

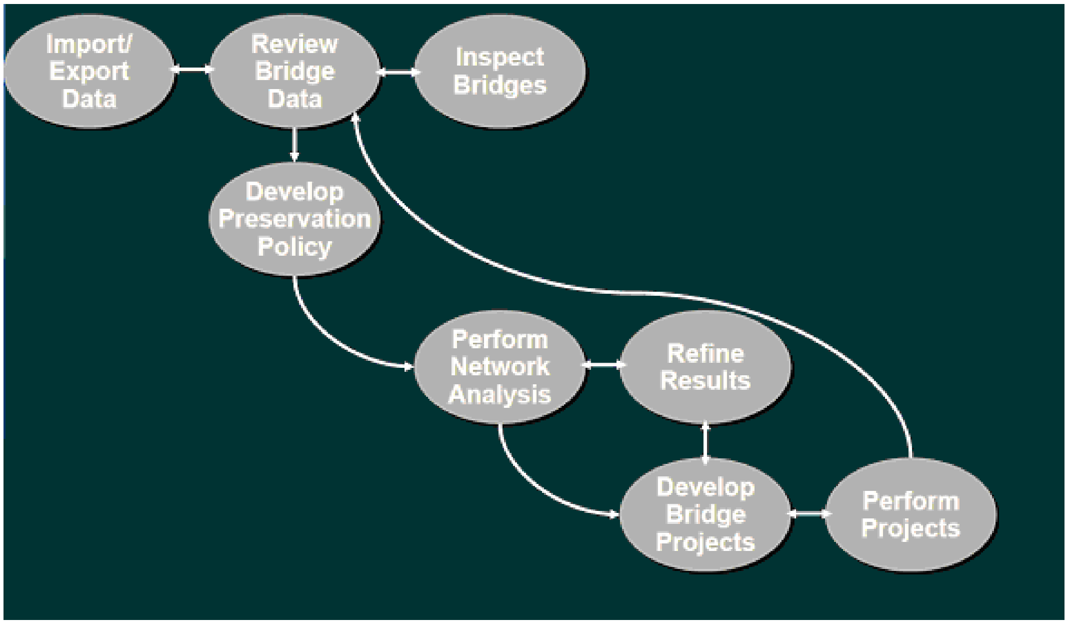

Figure 12: Pontis Analytical Bridge Management Process (Cambridge Systematics, Inc., 2004)

2.3.2.1 STRUCTURAL ELEMENTS

Pontis utilizes detailed data of a bridge in terms of its structural elements, which in turn allows for an accurate and effective analysis when developing predictive models and deterioration curves (Markow & Hyman, 2009). These structural elements are labeled "Commonly Recognized" (CoRe) elements due to their national recognition and use in highway bridge construction. CoRe elements and their descriptions' were established by bridge engineers from six State DOTs (California, Colorado, Minnesota, Oregon, Virginia and Washington) and the FHWA. Although CoRe element definitions originated in the Pontis methodology, they are not exclusive to Pontis, but rather give a consistent method for tracking bridge data for any BMS, enable data sharing between States, and provide a standard for relating element level inspection to NBIS condition ratings (AASHTO, 2001). While CoRe elements are the basis for the Pontis standard database, users are allowed to create additional customized elements (Michael Baker Jr., Inc.; Cambridge Systematics, Inc., 2009).

AASHTO CoRe elements are a breakdown of major bridge elements (deck, superstructure and substructure) to minor elements that collectively form the major elements. For example, CoRe elements that make up a steel superstructure may include girders, splices and lateral bracing as illustrated in Figure 13.

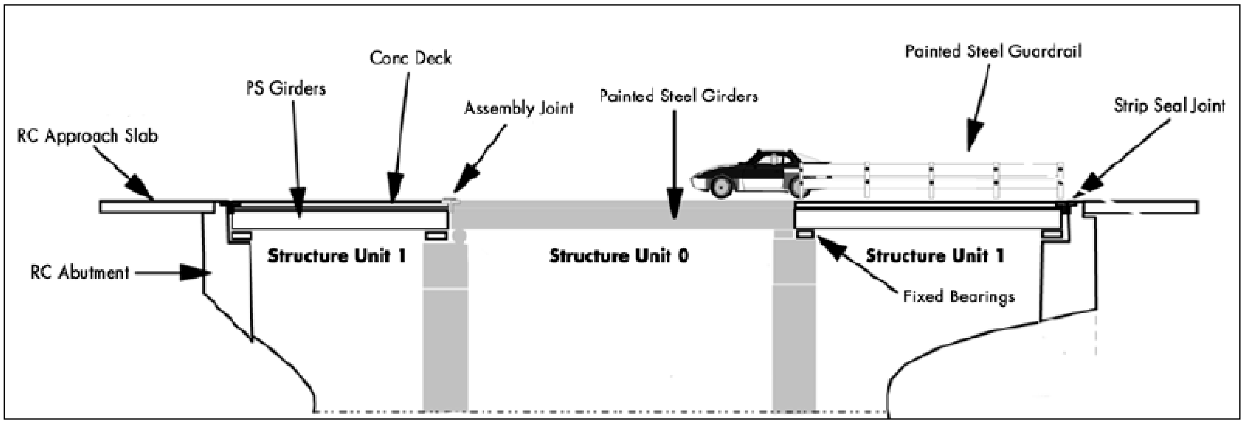

Figure 13: Structural Units and Elements in Pontis (Michael Baker Jr., Inc.; Cambridge Systematics, Inc., 2009, pp. 3-3)

Pontis users have the freedom to create their own elements, and if they elect to do so, are advised to follow a set of rules for determining elements as included in the AASHTO CoRe element guide. These rules assert that a single structural element can only incorporate parts of a bridge that are made of the same material, are expected to deteriorate at a similar rate and fashion and inventoried (quantitatively) with units that are easily accessed by the inspector and have meaningful interpretation at the network level (AASHTO, 2001).The guide also indicates that the CoRe elements may be divided into sub-elements if an agency deems it necessary for enhanced performance tracking.

Similar to the NBIS condition ratings discussed in Section 2.2.1, defects in the structural elements due to deterioration are defined by “condition states.” “Condition states for each element have been precisely defined in terms of the specific types of distresses that the elements can develop,” (Michael Baker Jr., Inc.; Cambridge Systematics, Inc., 2009, pp. 3-3). There are up to five condition states, where condition state one represents the best condition (no damage) and higher condition states represent the worst condition. Some elements have three condition states, while others may have four or five. However, it should be noted that per the recently published *AASHTO Guide Manual for Bridge Element Inspection 1st Edition*, all elements have four condition states.

The AASHTO CoRe element guide includes procedures for condition state language (AASHTO, 2001):

- Condition state language for an element cannot:
    - Include various kinds of distress unless it can be reasonably assumed that those listed symptoms of element distress migrate (both down and up) from one condition state to another in a predictable pattern; that they all can be remedied by the same set of feasible actions; that costs for those feasible actions are reasonably the same when correcting anyone of those listed distress characteristics; and that all hold the same consequence for the element if the "Do Nothing" option is selected.
    - Attempt to describe distress condition(s) in "good," "fair," and "poor" terms. Only relevant descriptive engineering terminology is acceptable.

"To the extent possible, elements and condition states should be defined in such a way that deterioration, actions and costs on one element are independent of deterioration, actions and costs on any other element" (AASHTO, 2001, p. 2). Immediately following the condition state description, a set of feasible improvement actions is provided to aid in the development of preservation strategies.

As an example the condition states and corresponding feasible actions for elements 112- Unpainted Steel Stringer and 321 - Reinforced Concrete Approach Slab are as follows (AASHTO, 2001):

- 112- Unpainted Steel Stringer
  - CS 1 - No corrosion; Action - Do nothing
  - CS 2 - Surface rust; Actions - Do nothing, Clean and paint
  - CS 3 - Measurable section loss; Actions - Do nothing, Clean and paint
  - CS 4 - Advanced corrosion with sufficient section loss; Actions - Do nothing, Rehab unit, Replace unit
- 321 Reinforced Concrete Approach Slab
  - CS 1 - No settlement or deterioration; Action - Do nothing
  - CS 2 - Minor cracking, spalls and settlement; Actions - Do nothing, Perform mud-jacking operations
  - CS 3 -Major cracks, heavy spalling and settlement; Actions - Do nothing, Place overlay, Replace unit
  - CS 4 -Broken slab, excessive settlement; Actions - Do nothing, Replace unit

The rate, at which an element deteriorates, moves from one condition state to another, is a function of the surrounding environmental characteristics. There are four environmental classifications in the *Pontis Release 4.5 and 5.1 User's Manual* (Michael Baker Jr., Inc.; Cambridge Systematics, Inc., 2009, pp. 3-3):

- Benign: No environmental conditions affecting deterioration.
- Low: Environmental conditions create no adverse impacts or are mitigated by past non-maintenance actions or highly effective protective systems.
- Moderate: Typical level of environmental influence on deterioration
- Severe: Environmental factors contribute to rapid deterioration. Protective systems are not in place or are ineffective.

2.3.2.2 ANALYTICAL PROCEDURE AND MODELING APPROACH

As seen by the list of major functions, modules, and Figures 11 and 12, the modeling and analysis process of Pontis is extensive and addresses several aspects of bridge management (Markow & Hyman, 2009). First, element-level inspection and data are necessary for Pontis' analyses and is managed by the inspection module. It should be noted that the element data requires conversion to NBIS item ratings when reported to the FHWA to help ensure consistency between State agencies so condition comparisons at the major bridge element level are feasible on a national scale (FHWA, 1995). For instance, the CoRe element ratings for the girders, splices and lateral bracing are combined into a single superstructure rating. Pontis is capable of performing the conversions, as well as computing other NBI condition indicators such as the Sufficiency Rating (Markow & Hyman, 2009).

In addition to managing inspection data Pontis is able to help agencies develop an optimal preservation policy, through a comprehensive analysis, that takes into account different improvement and rehabilitation actions(e.g., painting or modify bridge railing) applied to structural elements (e.g. steel girders or curbs) in every type of environment, at different stages of deterioration. Assuming that the users account for construction logistics and scheduling, the mathematically derived result is able to provide guidelines and realistic projections for a long term, network wide, investment strategy for maintaining bridges. Additionally, Pontis considers budget constraints as well as the costs and benefits for the prioritization and allocation of resources. Furthermore, the program allows agencies to account for their specific policies and practices (Michael Baker Jr., Inc.; Cambridge Systematics, Inc., 2009). An important distinction made in the preservation policy module is the separation of preservation from improvement. In the model, analysis is conducted for each function independently and preservation and improvement recommendations for specific bridges are then merged to generate the optimal preservation policy from the standpoint of network needs (Michael Baker Jr., Inc., 2009). The

Pontis Release 5.1 Technical Manual defines preservation and improvement as follows (Michael Baker Jr., Inc., 2009, p. 233):

> "Preservation management is the pursuit of the most efficient way to keep existing bridges in operation at their current level of service... It sidesteps the question of what the required level of service should be, or even whether the bridge should remain open. Instead, it assumes that operations must continue and that deterioration must be detected and remedied before operations are affected, at minimal cost."

> "Improvement management, on the other hand, addresses functional shortcomings, identifies instances where adequate [current] standards are not met, develops strategies to meet them, and prioritizes and sequences such improvements."

Three models, deterioration, cost, and optimization, fundamentally constitute the preservation module. The deterioration model depends on expert judgment to obtain probability based deterioration predictions of the structural elements when alternate maintenance actions (including no action) are completed. As new inspections are conducted and preservation actions taken, deterioration predictions change and are accounted for by an updating program within the deterioration model. Next, the cost model program is similar to the deterioration model because it relies on expert judgments to develop cost estimates and it is updated to account for actual costs. Finally, the optimization model combines the deterioration predictions and estimated costs to determine the most cost-effective improvement strategy. It conducts optimizations for each element at different stages of deterioration and as with the other models, may be updated to reflect changes in deterioration or costs (Michael Baker Jr., Inc.; Cambridge Systematics, Inc., 2009).

After inventory and inspection, data are recorded and an optimal preservation policy has been developed, users are able to run network level simulations and decision-support procedures. The simulations predict bridge preservation and functional improvement needs, take into consideration budget limits, estimate effect of future bridge enhancements and assess the condition of the entire bridge network (Markow & Hyman, 2009). Simulation results can be expressed in several ways as discussed in *NCHRP Synthesis 397* (Markow & Hyman, 2009, p. 22):

- Condition distributions of structure elements
- Predictions of structure needs and work that is projected to have been accomplished
- The Bridge Health Index (BHI), which is the ratio of the current value of all structure elements (based on their current distribution of condition states) as compared with the total value of all elements (assuming all are in their best condition state)
- Benefits to both agency and road users as the result of preservation and improvement actions; for example, improvements in the Health Index, and road-user benefits in terms of reduced travel time, vehicle operating, and accident related costs as the result of bridge improvements
- NBIS condition ratings for deck, superstructure, substructure, and culvert; deficiency status (Structurally Deficient or Functionally Obsolete); NBIS appraisal ratings; and calculation of the NBIS Sufficiency Rating
- Health Index of subsets of elements, eligibility for HBP funding, and detail information for individual structures

For further discussion of the customization options and detailed descriptions of available reports generated by Pontis, the reader is referred to the *Pontis Release 5.1 User and Technical Manuals* as well as *NCHRP Synthesis 397*.

The final major function of Pontis involves the development of projects for individual bridges, also known as project planning. Bridge projects emerge from recommendations of inspectors, field personnel, and the results of the aforementioned simulations, and are then assembled into programs (Markow & Hyman, 2009). Programs are a way of grouping projects based on characteristics such as period, status or type of work. They have start and end dates, and annual budges tied to specific funding sources (Michael Baker Jr., Inc.; Cambridge Systematics, Inc., 2009). After projects have been placed in programs, additional network-level scenarios can be run to refine results through adjustments in optimal preservation policies and other characteristics (Markow & Hyman, 2009).

2.3.2.3 BRIDGE HEALTH INDEX (BHI)

The Bridge Health Index (BHI) in Pontis is an economic indicator that estimates how much value the elements of a structure have depreciated as their condition has deteriorated over time. In other words, the BHI is the ratio of the sum of the Current Element Value (CEV_e) to the sum of the Total Element Value (TEV_e). Index values range from 0% being the lowest value, representing the worst condition and 100% indicating that the structure still has 100% of its original asset value representing a like new condition. If rehabilitations and repairs were conducted then the asset value for the element of interest would increase and thus increase the BHI of the bridge (Jiang & Rens, 2010).

As previously expressed, this research maintains that it is necessary that decision makers are aware of what elements are used and how they are utilized by their bridge evaluation and management techniques. Therefore, to help fully understand how a BHI is calculated, an explanation of the methodology, followed by example calculations, is provided for a hypothetical bridge. The BHI methodology is adapted from the *Pontis Release 5.1 Technical Manual* (Michael Baker Jr., Inc., 2009). First, the health index of an individual element is calculated according to the formula $H_e = \frac{\sum_s k_s q_s}{\sum_s q_s} \times 100\%$, where:

- H_e is the health index of an individual element
- s is the index of the condition state
- q_s is the element quantity in sth condition state

- k_s is a health index coefficient corresponding to the s^th^ condition state and is calculated by the formula: $k_s = \frac{n - s}{n - 1},\ s = 1,2,...,n \quad n = 3|4|5$, where n is the number of applicable condition states, which can be three, four, or five as per the AASHTO CoRe element guide.

Once all of the element health indices have been determined, the health index of an entire bridge is determined as the weighted average of the element health indices. Elements are weighted based on their total quantity and relative importance. The bridge index formula is $H = \frac{\sum_e H_e Q_e W_e}{\sum_e Q_e W_e}$, where:

- e is the index of an element
- Q_e is the total quantity of the element e on the bridge
- W_e with the weighting factor of the element e, which is determined by Pontis as either the sum of agency and user failure costs, or a coefficient explicitly assigned to the element multiplied the value of the most costly action for the element.

If the equation for H_e is substituted into the formula for H the following equation can be derived $H = \frac{\sum_e CEV_e}{\sum_e TEV_e} \times 100\%$, where $CEV_e = W_e \sum_s k_s q_s$ and $TEV_e = W_e \sum_s q_s$ represent the Current Element Value and the Total Element Value of the element respectively. Their summations represent the Current and Total Values of the entire bridge.

The following example (Table 10) is for a hypothetical steel girder bridge (250'-0" long and 43'-4" wide) with a concrete deck, integral concrete abutments, and concrete multi-column bents. The example also assumes the failure costs are used to determine the weighting factor.

Table 10: Elements and Condition States for Hypothetical Bridge: Adapted from (Michael Baker Jr., Inc., 2009)

Element Description	Units	Total Quantity	CS 1	CS 2	CS 3	CS 4	CS 5	Failure Cost
Concrete Deck - Protected with Coated Bars (26)	EA	1 (10833 SF)		1				$145,000
Compression Joint Seal (302)	LF	87 (2 seals x 43.5')	17	40	30			$30
Open Girder - Unpainted (106)	LF	1237.5 (5 x 247.5')	805	247.5	185			$300
RC Cap- Bent (234)	LF	80 (2 caps x 40')	64	16				$450
RC Column - Bent (205)	EA	120 (6 col. x 20')	96	24				$200
RC Abutment (215)	LF	87 (2 abut x 43.5')	60	27				$375

Given that $H_e = \frac{\sum_s k_s\, q_s}{\sum_s q_s} \times 100\%$ the health index of the individual elements are as follows:

$$H_{26} = \frac{k_2\, q_2}{q_2} \times 100\% \Rightarrow \frac{\frac{5-2}{5-1} \times 1}{1} \times 100\% \Rightarrow \frac{0.75 \times 1}{1} \times 100\% = 75\%$$

$$H_{302} = \left(\frac{k_1\, q_1 + k_2\, q_2 + k_3\, q_3}{q_1 + q_2 + q_3} \right) \times 100\% \Rightarrow \left(\frac{1 \times 17 + 0.5 \times 40 + 0 \times 30}{17 + 40 + 30} \right) \times 100\% \Rightarrow \frac{37}{87} \times 100\% = 42.5\%$$

$$H_{106} = \left(\frac{k_1\, q_1 + k_2\, q_2 + k_3\, q_3}{q_1 + q_2 + q_3} \right) \times 100\% \Rightarrow \left(\frac{1 \times 805 + 0.67 \times 247.5 + 0.33 \times 185}{805 + 247.5 + 185} \right) \times 100\% \Rightarrow$$

$$\Rightarrow \frac{1031.65}{1237.5} \times 100\% = 83.3\%$$

$$H_{234} = \left(\frac{k_1\, q_1 + k_2\, q_2}{q_1 + q_2} \right) \times 100\% \Rightarrow \left(\frac{1 \times 64 + 0.67 \times 16}{64 + 16} \right) \times 100\% \Rightarrow \frac{74.7}{80} \times 100\% = 93.3\%$$

$$H_{205} = \left(\frac{k_1\, q_1 + k_2\, q_2}{q_1 + q_2} \right) \times 100\% \Rightarrow \left(\frac{1 \times 96 + 0.67 \times 24}{96 + 24} \right) \times 100\% \Rightarrow \frac{112}{120} \times 100\% = 93.3\%$$

$$H_{215} = \left(\frac{k_1\, q_1 + k_2\, q_2}{q_1 + q_2} \right) \times 100\% \Rightarrow \left(\frac{1 \times 60 + 0.67 \times 27}{60 + 27} \right) \times 100\% \Rightarrow \frac{78}{87} \times 100\% = 90\%$$

Once the health index of individual elements has been calculated the health index for the entire bridge, given by the equation $H = \frac{\sum_e H_e Q_e W_e}{\sum_e Q_e W_e}$, can be determined. For brevity only elements 26, 106 and 205 will be shown in the ensuing example.

$$H_{20,106,205} = \left(\frac{H_{26}Q_{26}W_{26} + H_{106}Q_{106}W_{106} + H_{205}Q_{205}W_{205}}{Q_{26}W_{26} + Q_{106}W_{106} + Q_{205}W_{205}} \right) \Rightarrow$$

$$\Rightarrow \left(\frac{75\% \times 1 \times \$145{,}000 + 83.3\% \times 1237.5 \times \$300 + 93.3\% \times 120 \times \$200}{1 \times \$145{,}000 + 1237.5 \times \$300 + 120 \times \$200} \right) \Rightarrow$$

$$\Rightarrow \left(\frac{\$108{,}750 + \$309{,}495 + \$22{,}400}{\$145{,}000 + \$371{,}250 + \$24{,}000} \right) \Rightarrow \left(\frac{\$440{,}645}{\$540{,}250} \right) = 81.6\%$$

As previously noted the numerator and denominator can be substituted by the CEV_e and the TEV_e respectively, where $CEV_e = W_e \sum_s k_s q_s$ and $TEV_e = W_e \sum_s q_s$. For elements 26, 106 and 205 the CEV_e and TEV_e are subsequently calculated by

$$CEV_{26} = \$145{,}000 \times 0.75 \times 1 = \$108{,}750$$

$$CEV_{106} = \$300 \times \left(1 \times 805 + 0.67 \times 247.5 + 0.33 \times 185\right) = \$300 \times 1031.9 = \$309{,}570$$

$$CEV_{205} = \$200 \times \left(1 \times 96 + 0.67 \times 24\right) = \$200 \times 112 = \$22{,}400$$

$$TEV_{26} = \$145{,}000 \times 1 = \$145{,}000$$

$$TEV_{106} = \$300 \times \left(805 + 247.5 + 185\right) = \$300 \times 1237.5 = \$371{,}250$$

$$TEV_{205} = \$200 \times \left(96 + 24\right) = \$200 \times 120 = \$24{,}000$$

$$H = \frac{\sum_e CEV_e}{\sum_e TEV_e} \times 100\% \Rightarrow \left(\frac{\$108{,}750 + \$309{,}570 + \$22{,}400}{\$145{,}000 + \$371{,}250 + \$24{,}000} \right) \Rightarrow \left(\frac{\$440{,}720}{\$540{,}250} \right) = 81.6\%$$

The values shown in Table 11 are a summary of the CEV_e and TEV_e for the entire bridge.

Table 11: CEVe, TEV_e and BHI for Theoretical Bridge: Adapted from (Michael Baker Jr., Inc., 2009)

Element Description	**CEV_e**	**TEV_e**
Concrete Deck - Protected with Coated Bars (26)	$108,750	$145,000
Compression Joint Seal (302)	$1,110	$2,610
Open Girder - Unpainted (106)	$309,570	$371,250
Reinforced Concrete Cap- Bent (234)	$33,590	$36,000
Reinforced Concrete Column - Bent (205)	$22,400	$24,000
Reinforced Concrete Abutment (215)	$29,365	$32,625
Total	$503,785	$611,485

$$H = \frac{\sum_e CEV_e}{\sum_e TEV_e} \times 100\% \Rightarrow \left(\frac{\$503{,}785}{\$611{,}485}\right) \times 100\% = 82.4\%.$$

In summary, Pontis employs engineering, statistical and economic models, that integrate logic, mathematical formulas, heuristic rules, linear optimization, statistics methods and simulation algorithms (Michael Baker Jr., Inc., 2009, p. 231). There are five models that interact with several databases as well as other models within the program as seen if Figure 14.

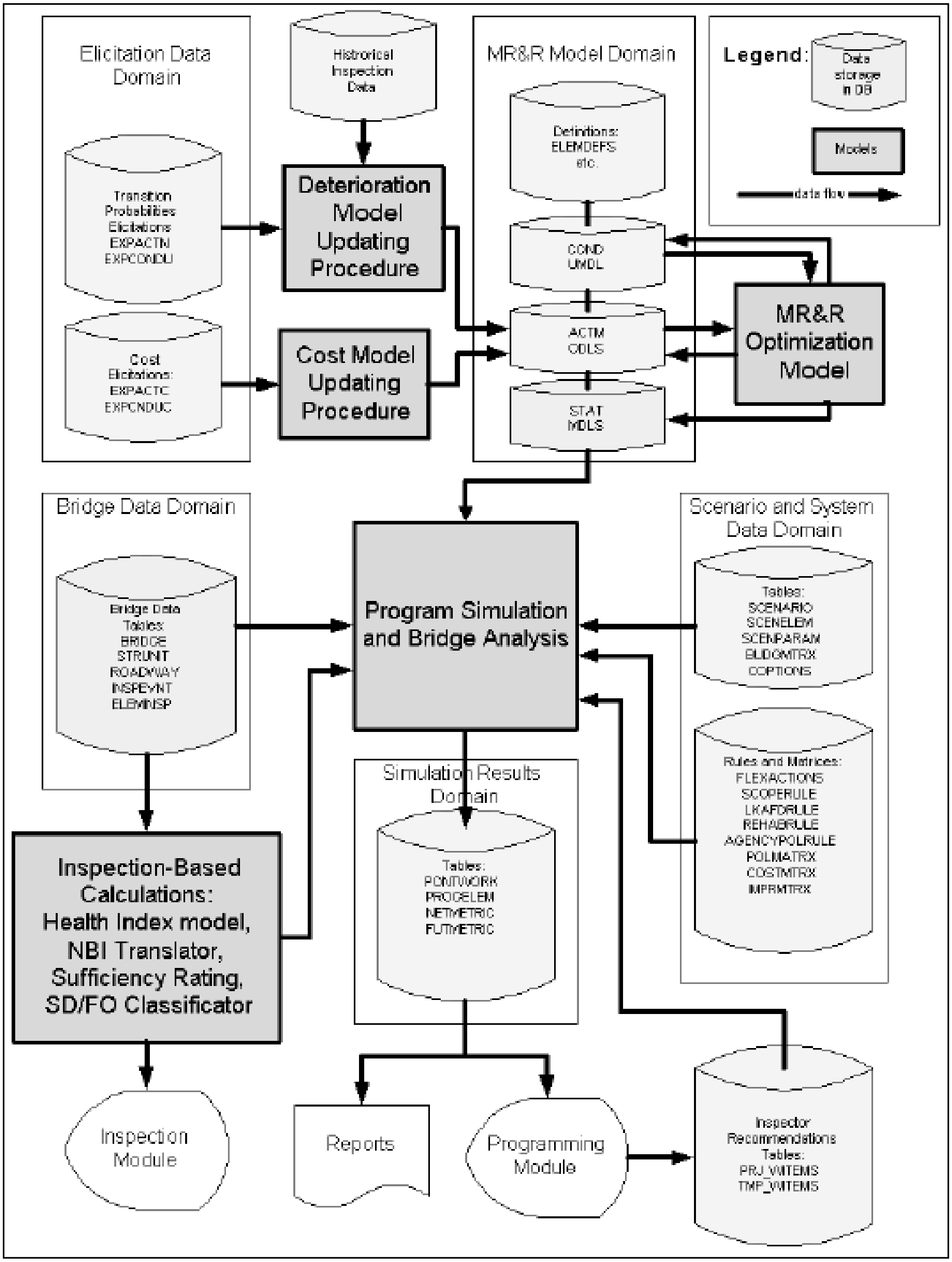

Figure 14: Pontis Models and Interaction with Database and Modules (Michael Baker Jr., Inc., 2009)

2.4 Research in Bridge Management

Literature reviews for this research encompassed several publications in the field of asset management, with specific emphasis on bridge management, and include but are not limited to, reports, conference proceedings, and journal and magazine articles. In an effort to condense this document, the researcher summarized and included only a handful of the publications in this section. Refer to Appendix A for an extensive list of other relevant publications cited for further study and additional reading.

2.4.1 Multi-Objective Maintenance Planning Optimization of Deteriorating Bridges Considering Condition, Safety, and Life-Cycle Cost

The authors of this paper observed that the many current BMS, such as Pontis, focus on "minimizing the expected cumulative maintenance costs over a specified time while treating other important bridge performance criteria as relevant constrains in the optimization process" (Frangopol & Liu, 2005, p. 833). They note that while the "unique optimal maintenance solution as is obtained from the traditional life-cycle cost optimization approaches" (Frangopol & Liu, 2005, p. 833)is valuable, the singular solution may not meet the specific needs of a bridge manager. Furthermore they concluded that a "set of alternative maintenance solutions … comprises the best possible tradeoff among all competing objectives under consideration" (Frangopol & Liu, 2005, p. 833). Therefore, they formulated a multi-objective optimization problem that utilizes the condition of a bridge, the safety level of a bridge, and life-cycle maintenance cost as the separate objectives. The primary goal of the study was to develop an automated procedure that produces the optimal maintenance solution for a bridge when considering multiple criteria. Using a genetic algorithm, this study achieved this goal and produced a procedure to improve the condition index and the safety; and reduce the life-cycle costs.

The condition index "is a continuous generalization of the visual inspection-based and discrete-valued quantities that are adopted in current bridge management systems" (Frangopol & Liu, 2005, p. 834). In other words, the study is using inspection conditions states similar to those defined in the *Recording and Coding Guide* (FHWA, 1995), *AASHTO Guide for CoRe Elements* (AASHTO, 2001) or the new *AASHTO Guide Manual* (AASHTO, 2011) for the condition index as discussed earlier in this chapter. The safety index is the "ratio of available to required live load-carrying capacity" (Frangopol & Liu, 2005, p. 834). This is effectively the same as the inventory and operating ratings as found in the *Recording and Coding Guide* (FHWA, 1995). The study then deteriorates the condition index and safety index using a multi-linear used a multi-linear computation model to deteriorate the condition and safety indices.

Finally, upon the development of the procedure, the authors tested different maintenance strategies on a collection of reinforced concrete crossheads in the United Kingdom. The procedure found 1,851 solutions, and identified and labeled nine of the optimized solutions in two and three-dimensional plots, to illustrate the trade-off analysis when selecting a final maintenance solution.

2.4.2 Novel Approach for Multi-Criteria Optimization of Life-Cycle Preventive and Essential Maintenance of Deteriorating Structures

This paper presents an automated multi-objective optimization process based on multiple performance indicators (unavailability, redundancy) as well as life cycle costs to develop a maintenance plan for structures. The paper notes that performance indicators are forewarning of the need for maintenance activity when they reach their threshold, which ensures the safety and integrity of structures. The authors list several potential performance indicators, identified through a literature review as "the point-in-time reliability index, the point-in-time probability of system failure and frequency, the cumulative probably of failure, the lifetime probability of failure or unavailability, and the condition and safety indexes" (Frangopol & Okasha, 2010, p. 1009). This research used performance indicators (lifetime functions of unavailable and redundancy) for determining both preventive and essential maintenance decisions at regular and irregular intervals. Preventive maintenance is defined as time-based maintenance "applied at pre specified time instants over the life-cycle of the structure" (Frangopol & Okasha, 2010, p. 1009), while essential maintenance is performance-based and "applied when some performance indicators are predefined target values" (Frangopol & Okasha, 2010, p. 1009).

The stated optimization problem developed in this research, solved using genetic algorithms, and had several goals that included:

> "handle regular and irregular time-interval PM [preventative maintenance]; handle EM [essential maintenance] only, PM [preventative maintenance] only, and both EM [essential maintenance] and PM [preventative maintenance] combined; handle multiple PM [preventative maintenance] types and multiple EM [essential maintenance] types; and treat EM [essential maintenance] as performance-based" (Frangopol & Okasha, 2010, p. 1010).

This study used Colorado Bridge E-17-AH as a case study for this research. The bridge consists of three simple spans of rolled steel girders with a reinforced concrete deck and an asphalt overlay. The optimization results are presented graphically in the paper

The overall premise, of the research in Sections 2.4.1 and 2.4.2, that only utilizing a single rating or index (i.e. objective) has shortcomings, and a better approach is to develop a BMS that considers several bridge characteristics and incorporates the valuable expertise and opinions of bridge management engineers, coincides with the basis of this research. However, there are some distinct differences. First, the overall goal is to develop a multi-objective optimization procedure not just determining what objectives (components) should be used. Secondly, the studies do not identify any specific items that make up the objectives (components). For example, it does not specify if the condition index is related constructed of the deck, superstructure and/or substructure items, but rather objective themselves (condition index and safety index) relate more to items as defined in this research (i.e. superstructure and inventory rating). Additionally, the authors did not obtain the opinions of bridge managers and decision makers when determining the maintenance objectives (components), nor did they determine the relative importance between the objectives. Finally, it does not seem to address customizability by the end user.

2.4.3 Multi-Objective Optimization for Bridge Management Systems

The overall purpose of the research summarized in this report (NCHRP 590) is to develop a BMS that optimizes bridge preservation and maintenance work as it relates to specific actions and investments, and the stage in a bridge's life cycle they occur. The motivation for this research and development of the resulting BMS are due to past experience that:

> "suggests that bridge investment decision made only on the basis of lowest cost yield unsatisfactory results. Therefore, bridge agencies have expressed a need to enhance current decision-making methodologies to include other performance criteria, such as bridge condition, safety, traffic flow disruption and vulnerability. That way, more balanced, rational, defensible and cost-effective decisions can be made and better investigation of trade-offs between performance criteria can be carried out." (Thompson, Patidar, Labi, & Sinha, 2007, p. 1)

To achieve their stated goals, the authors defined five objectives, evaluated by multiple performance measures as seen in Table 12.

Table 12: Goal and Performance Measures (Thompson, Patidar, Labi, & Sinha, 2007)

Goals	Performance Measures
1. Preservation of Bridge Condition	(a) Condition Ratings (NBI 58-60, 62)
	(b) Health Index
	(c) Sufficiency Rating
2. Traffic Safety Enhancement	(a) Geometric Rating/Functional Obsolescence
	(b) Inventory Rating or Operating Rating
3. Protection from Extreme Events	(a) Scour Vulnerability Rating
	(b) Fatigue/Fracture Criticality Rating
	(c) Earthquake Vulnerability Rating
	(d) Other Disaster Vulnerability Rating (Collision, Overload, Human-Made)

4. Agency Cost Minimization	(a) Initial Cost
	(b) Life-Cycle Agency Cost
5. User Cost Minimization	(a) Life-Cycle User Cost

Next, the study surveyed bridge management experts (NCHRP Panel 12-67) to determine the relative importance of the performance criteria and the objectives in the previous table. After that, they determined value and utility functions for each performance measure. Finally, the authors utilized the objectives, performance measures and their corresponding relative weights to generate an objective function, and optimized the function at both bridge and network levels.

The optimization problem in the report is a multi-choice, multi-dimensional knapsack problem (MCMDKP), analyzed using incremental utility-cost (IUC) ratio, Lagrangian and pivot complement approaches. The research team then tested the solutions using data from Florida DOT. Finalized results were implemented to develop a framework to form a software application called Multi-Objective Optimization System (MOOS).

While this study's ultimate purpose is significantly different, part of the research conducted to perform this study resembles the underlying theme of this research (determining bridge management components and items that make up those components as discussed in Chapter 1. However, there are some distinct differences. First, it appears that the survey was only used to get the input of the bridge management experts to determine the relative weights not the actual objectives and related performance measures (components and items). In addition, although the authors used direct weighting and the Analytic Hierarchy Process (AHP) (AHP will be further discussed in the following chapter) as methods for determining the relative weights, they used the Delphi technique for the group decision and not the geometric mean as recommend for the AHP as discussed in Section 3.3.2. Finally, it does not appear that the MOOS software application allows for user customization of the objectives and performance measures.

As recognized by the literature reviewed in this section (Section 2.4), there is a need to use multiple criteria (defined as components in this research) to conduct trade off analysis to aid decision makers in optimizing available resources with maintenance, rehabilitation and replacement decisions. Furthermore, the literature suggests that there are a number of methods and applications used in determining the criteria that are utilized used in the optimization process.

CHAPTER 3: METHODOLOGY

This chapter presents the full and detailed methodology of a two-part survey of expert opinions with the stated objectives of (i) identifying the appropriate items that make up each bridge management component and (ii) determining the relative importance of those items as well as the bridge management components as represented by weighting factors. The researcher developed a list of proposed items that make up each bridge management component for the first part of the survey. In addition, this research utilizes a decision analysis procedure called the Analytic Hierarchy Process (AHP. Therefore, an in-depth discussion about AHP is provided as well as how its use in developing the second part of the survey in order to determine the relative weighting factor for the identified items.

3.1 BRIDGE MANAGEMENT SYSTEMS

For decision makers in a transportation agency determining the optimal allocation of resources between competing bridges is a challenge. This is especially true when bridges continue to deteriorate and available resources (specifically funding) to address preservation and improvement needs are limited. Bridge Management Systems (BMS) are a method "designed to optimize the use of available resources for the inspection, maintenance, rehabilitation and replacement of bridges" (FHWA, 1995, p. x). BMSs interface with database records that encompass the characteristics and current condition of bridges on a transportation network; and help the user(s) decipher the data so they are able to evaluate and determine how to best allocate available resources to address the needs of several structures. The information contained within the database is gathered through routine inspections as discussed in Section 1.2.

Bridges are essential since they provide crossings at locations where an alternative route would be an inconvenience for the user, potentially adding considerable travel time and cost. Additionally, the preservation and improvement of bridges is very costly and thus the financial decisions made to improve the condition and/or the serviceability of a bridge is of the utmost importance, not only to account for available funds but also to ensure a safe and effective transportation system (Markow & Hyman, 2009). Many transportation agencies recognize this as well as the "benefits of detailed condition assessments through the use of the raw inspection information, expanded performance measures, and bridge management system deterioration forecasting and evaluation" (AASHTO, 2011, p. ix), and have developed their own BMSs.

3.1.1 Motivation for the Development of Bridge Management Components

Based on the discussion in Sections 1.3 and 1.4 it is evident that any decision process that only involves a single rating, such as the Sufficiency Rating or a BHI, to manage bridges will have shortcoming and drawbacks, and that there currently is not a BMS that encompasses the needs of all transportation agencies. With this sentiment there are several bridge managers, agencies, and private companies attempting to develop a BMS that meets their specific needs and is effective at aiding in the decision making process. The purpose of this research is to investigate the concept of separating bridge related items from a single rating or index (i.e. Sufficiency Rating or Bridge Health Index) and then categorizing them into more usable bridge management components (i.e. Structural Condition, Impact on Public and Hazard Resistance) by determining the appropriate items within each component as well as the relative weighting factor associated with each item. By breaking down a single rating into multiple components decision makers in the industry would benefit by having another methodology for completing their bridge management analysis. Once the bridge management components are identified, transportation agencies may utilize them in a variety of ways to develop BMSs. Note that the motivation for this research is adapted from the BMS being considered by WYDOT as discussed in Section 1.3.

3.2 Identifying the Items for Each Component

Items that structure a bridge management component can be a major or minor element of a bridge (e.g. deck, girder, column, etc.), a characteristic of the bridge (e.g. vertical clearance, span length, roadway width, etc.) or an external feature that is associated with the bridge (e.g. seismic category, detour length, traffic volume, etc.).

A survey questionnaire will be sent to professionals and experts in the field of bridge management. Responses from survey participants will be used to verify or change items within each list. The next few sections deal with identifying lists of recommended items for each bridge management component, along with the approach and reasoning for their selection.

3.2.1 Lists of Proposed Items

Selection of the proposed items is based on background knowledge and an extensive literature review of the *NBIS Recording and Coding Guide*, the *AASHTO Guide for Commonly Recognized (CoRe) Elements*, and the recently published *AASHTO Guide Manual for Bridge Element Inspection 1st Edition*.

As discussed in Chapter 2 the *Recording and Coding Guide* contains over 100 inspection items and guidelines, which every State transportation agency is required by the FHWA to use to assess the condition and composition of bridges within their State.

Prior remarks on CoRe elements pointed out that they are a breakdown of major bridge elements into minor elements. Many transportation agencies inspect bridges using CoRe elements and then combine the appropriate elements to generate NBIS item ratings for reporting to the FHWA, some by means of a conversion program developed at the University of Colorado in 1997 (Hearn, Cavallin, & Frangopol, 1997).

The new *AASHTO Guide Manual for Bridge Element Inspection* contains improvements on the *AASHTO Guide for Commonly Recognized (CoRe) Elements* “to fully capture the condition of the elements by reconfiguring the element language to utilize multiple distress paths within the defined condition states” (AASHTO, 2011, pp. 1-1). Moreover, it presents a comprehensive set of elements designed to accommodate the needs of many different agencies (AASHTO, 2011). The manual breaks elements of a bridge into two types, National Bridge Elements (NBE) and Bridge Management Elements (BME). The NBEs “represent the primary structural” elements and the BMEs are elements “typically managed by agencies utilizing BMSs” (AASHTO, 2011, pp. 1-1).

3.2.1.1 PROPOSED LIST FOR STRUCTURAL CONDITION COMPONENT

The objective of the structural condition component is to isolate elements of a bridge that deteriorate over time to accurately measure the structural adequacy of a bridge. This may aid bridge managers in make bridge preservation and improvement decisions. The proposed items for this component, as identified through a thorough literature review and the experience of the author, are as follows:

1) **Deck/Slab** – The deck on a bridge or slab superstructure transfer loads to the supporting superstructure or substructure elements respectively. Examples include a timber deck, steel deck, reinforced concrete deck, and reinforced concrete superstructure. It should be noted that the Deck/Slab item does not include protective systems such as wearing surfaces. The Deck/Slab is classified as a NBE by the *AASHTO Guide Manual for Bridge Element Inspection* and is item 58in the *FHWA Recording and Coding Guide.*

2) **Protective Systems** – Protective systems such as wearing surfaces or protective coatings are used to extend the useful life of bridge elements. This item is included in item 58 in the *FHWA Recording and Coding Guide* and a BME in the *AASHTO Guide Manual*.

3) **Approach Slabs** – This item consists of any type of approach slab a bridge may have. Approach slabs are categorized as BME by the *AASHTO Guide Manual*. It is common for approach slabs to need either repaired or replaced. In addition, this item is not included in *FHWA Recording and Coding Guide* and therefore is not used to calculate the Sufficiency Rating.

4) **Bridge Railing** – Bridge railings include metal railings, concrete railings, timber railings, etc. The bridge railing is categorized as NBE by the *AASHTO Guide Manual*. Bridge railings are not included in FHWA Recording and Coding Guide and therefore are not used to calculate the Sufficiency Rating.

5) **Joints**– Joints include all expansion devices such as strip seals, compression seals, open joints, etc. Like protective systems, joints are categorized as BME by the *AASHTO Guide Manual*. It is common for joints to need either repaired or replaced and are not included in *FHWA Recording and Coding Guide* and therefore are not used to calculate the Sufficiency Rating.

6) **Superstructure** – This includes all of the structural elements that make up the superstructure. Examples of superstructure elements include girders or beams, splice plates, lateral bracing (e.g. cross frames and diaphragms), stiffeners, stringers, floor beams, gusset plates, cables, and built up members such as truss members and arch members. The superstructure is classified as a NBE by the *AASHTO Guide Manual for Bridge Element Inspection* and is item 59 in the *FHWA Recording and Coding Guide.*

7) **Bearings** – Bearings include all bearing devices such as fixed bearings, rocker bearings, elastomeric bearings, etc., and are categorized as NBE by the *AASHTO Guide Manual.*

8) **Substructure** – The substructure consists of all structural elements that represent the substructure such as abutments and bents/piers, which have several elements (i.e. cap, back wall, wingwalls, pedestals, columns, footings etc.). In addition, any effects from settlement would be included under this item. The substructure is classified as a NBE by the *AASHTO Guide Manual for Bridge Element Inspection* and is item 60 in the *FHWA Recording and Coding Guide.*

9) **Inventory Rating** – An inventory rating by definition is the load level that a bridge can safely support indefinitely (FHWA, 1995). Inventory ratings are generally calculated for the superstructure, but can be calculated for substructures as well. The inventory rating is item 66 in the *FHWA Recording and Coding Guide.*

10) **Posting** – If a bridge is posted or closed due to deficiencies, whether they are from deterioration over time or an event that caused serious damage, such as an earthquake, flood or vehicular impact, the posting should notably influence the structural condition. Without this item, the poor structural capacity of the bridge may not be reflected in the overall score for structural condition. Posting is item 41 in the *FHWA Recording and Coding Guide.*

3.2.1.2 PROPOSED LIST FOR IMPACT ON PUBLIC COMPONENT

The goal of the impact on public component is to evaluate how bridge attributes affect the traveling public and influence bridge management. Identifying these items may help decision makers prioritize bridgework. The proposed items for this component, as identified through a thorough literature review and the experience of the author, are as follows:

1) **Deck Geometry** – Assesses how the bridge conforms to current design and safety standards and considers the bridge roadway width and the vertical clearance over the bridge. As described by the FHWA *Recording and Coding Guide* this item is "used to

evaluate a bridge in relation to the level of service which it provides on the highway system of which it is a part" (FHWA, 1995, p. 45). Deck geometry is NBIS item 68.

2) **Underclearances, Vertical and Horizontal** – Measures how the bridge conforms to current design and safety standards in regards to the horizontal and vertical clearances under the bridge. As described by the FHWA *Recording and Coding Guide* this item is "used to evaluate a bridge in relation to the level of service which it provides on the highway system of which it is a part" (FHWA, 1995, p. 45). An underclearance, vertical and horizontal is NBIS item 69.

3) **Approach Roadway Alignment**– Evaluates how the alignment of the roadway approaches to the bridge relate to the general highway alignment for the section of highway the bridge is on (FHWA, 1995). Approach roadway alignment is NBIS item 72.

4) **Detour Length**– Detour length is included because alternative routes are an inconvenience for the user and it may add considerable travel time and cost. Detour length is item 19 in the *FHWA Recording and Coding Guide.*

5) **Average Daily Traffic (ADT) and Average Daily Truck Traffic (ADTT)** – The volume of traffic is an indication about how essential a bridge is to the traveling public. NBIS items 29 and 109, ADT and ADTT, account for the volume of traffic that is seen by a bridge.

6) **STRAHNET Designation**– Location and designation on the national highway system may suggest how important it is for abridge to remain open. There are five fractions of the NHS, which include the Interstate System, principal arterials important for commerce, the Strategic Highway Network (STRAHNET), STRAHNET connectors, and intermodal connectors (Federal Highway Administration (FHWA) and Federal Transit Administration (FTA), 2008). STRAHNET is a "system of highways which are strategically important to the defense of the United States" (FHWA, 1995, p. ix). For this reason item 100 in the NBIS, STRAHNET Designation, is included.

7) **<u>Bridge Railing</u>** – Bridge railing, under Impact on Public, is an evaluation as to whether or not the bridge railing and its related parts are up to current design and safety standards rather than the actual condition of the railing as measured in the Structural Condition component. This designation of bridge railing is found in the *Recording and Coding Guide* under item 36A and states

> "factors that affect the proper functioning of bridge railing are height, material, strength, and geometric features. Railings must be capable of smoothly redirecting an impacting vehicle. Bridge railings should be evaluated using the current AASHTO Standard Specifications for Highway Bridges, which calls for railings to meet specific geometric criteria and to resist specified static loads without exceeding the allowable stresses in their elements. Bridge railing should be crash tested per FHWA policy. Railings that meet these criteria and loading conditions are considered acceptable" (FHWA, 1995, p. 19).

8) **<u>Posting</u>** – If a bridge is posted or closed due to deficiencies, it may influence the traveling public by inducing route restrictions on heavy vehicles. Posting is item 41 in the *FHWA Recording and Coding Guide.*

3.2.1.3 Proposed List for Hazard Resistance Component

The objective of the hazard resistance component is to evaluate how attributes and external factors affect the vulnerability of a bridge in regards to probability of an event as well as probability of failure. Potential events such as earthquakes, floods, or collapse could be detrimental to a bridge. Therefore, determining a bridges level of hazard resistance may aid bridge managers complete their bridge management analysis. The proposed items for this component, as identified through a thorough literature review and the experience of the author are as follows:

1) **<u>Scour Critical</u>**–This item is to identify the status of a bridge regarding its vulnerability to scour based on a scour analysis. During a flood event there is a possibility for scour to occur and cause the loss of a bridge. Scour critical is item 113 in the *FHWA Recording and Coding Guide.*

2) **<u>Channel and Channel Protection</u>**–This item describes the physical conditions associated with the flow of water beneath the bridge such as stream stability and the condition of the channel. Inadequate channel protection or an unstable channel can facilitate erosion can severely weaken the substructure and/or foundation and possibly cause the loss of a bridge. Channel and channel protection is item 61 in the *FHWA Recording and Coding Guide.*

3) **<u>Waterway Adequacy</u>**–This item appraises the channel with respect to passage of flow through the bridge and the potential for overtopping. Again, this item is important as it relates to potential flood events. Waterway adequacy is item 71 in the *FHWA Recording and Coding Guide.*

4) **<u>Seismic Zone</u>** – The seismic zone or seismic design category (SDC) is related to the probability a bridge will undergo a seismic event along with the magnitude or intensity of that event. This item is not included in *FHWA Recording and Coding Guide* or the *AASHTO Guide Manual for Bridge Element Inspection.*

5) **<u>Seismic Design</u>** – This item is intended to capture a bridges ability to withstand a seismic event based on if it was designed or retrofitted for its appropriate seismic category. Seismic design is an important factor because of recent changes in how seismic zones are determined. These changes have placed many bridges in a higher seismic category. Thus, a bridge that was constructed several years ago may not incorporate certain seismic design considerations and will not perform as well during a seismic event. Seismic design is not included in *FHWA Recording and Coding Guide* or the *AASHTO Guide Manual for Bridge Element Inspection.*

6) **<u>Structure Type</u>** – This item is included because certain structure types require a more complex engineering analysis and design and may be more vulnerable to external hazards (i.e. fracture critical details, submerged elements, suspension bridges, arches etc.). As

seen with the I-35W bridge collapse in Minnesota, a “fracture critical” structure can collapse without any warning. This item relates to NBIS items 43 and 92.

7) **Underclearances, Vertical and Horizontal** – This item is included under the hazard resistance because if the underclearances are inadequate the potential for a vehicular or vessel impact increases. An underclearance, vertical and horizontal is NBIS item 69.

3.2.2 SEEKING PROFESSIONAL AND EXPERT OPINIONS FINALIZE ITEMS FOR EACH COMPONENT

As previously stated the objective of this research is to identify the items that should be included under each component, along with their related weighting factors. This will be conducted through two consecutive surveys of industry professionals and experts. The first survey will explain the concept of bridge management components, their proposed items, and the objective of each component as discussed in previous sections. Participants will review the proposed items and validate them or make restructuring suggestions. The solicitation email, background information, and survey questionnaire that will be sent to participants are found in Appendix B, Appendix C and Appendix D respectively.

Participants will check either an “agree” box, a “disagree” box, or a “disagree” box with an option to suggest the item be moved to a different component. If the ratio of respondents that check “agree” boxes to the total number of respondents is greater than the ratios for respondents that check “disagree” and “disagree and move”, then the associated item will be considered validated under its component. However, if one of the other ratios governs, then the item will either be removed completely or moved under a different component.

Once the items for each component are finalized, the participants will determine the appropriate weighting factor for each item. This will be done through a second survey using the Analytic Hierarchy Process as discussed in the following section.

3.3 IDENTIFYING ITEMS' RELATIVE IMPORTANCE AS REPRESENTED BY WEIGHTING FACTORS

The items for Structural Condition, Impact on Public and Hazard Resistance components will be determined based on the statistical results from the initial survey. Next, the same participants will establish the relative importance of the items as represented as weighting factors by conducting pairwise comparisons. In addition to the primary purpose as mentioned in Section 1.5, this research will also determine the relative importance of the components, through pairwise comparisons, and assign their associated weighting factor. Pairwise comparisons will populate a reciprocal matrix as established by the Analytic Hierarchy Process. The Analytic Hierarchy Process is a multi-criteria decision analysis method and is further discussed in subsequent sections.

3.3.1 ANALYTIC HIERARCHY PROCESS (AHP)

In general people make decisions based on what criteria they feel are the most important, basing their feelings on previous experience, external advice, intuition and ability to rationalize (Saaty T. L., 1989). They believe that "clear-headed, logical thinking is [the] only sure way to solve problems" (Saaty T. L., 1994, p. 20), however convincing others that their decision is the correct one is difficult and simply citing their own intuition may not be adequate (Saaty T. L., 1989). Multi-criteria decision analysis methods aid decision makers in logically reasoning through the advantages and disadvantages of decision alternatives. The Analytic Hierarchy Process is a multi-criteria decision analysis method that "assists people in organizing their thoughts and judgments to make more effective decisions, [while providing] … the objective mathematics to process the inescapably subjective and personal preferences on an individual or group in making decisions" (Saaty & Vargas, 2001, p. 12 & 27).

Thomas L. Saaty developed the Analytic Hierarchy Process (AHP) in the early 1970's at the University of Pennsylvania (Saaty R. W., 1987). Multi-criteria decision making is the primary use for the AHP and has applications in several areas such as economics, planning, energy, conflict resolution, budgeting, resource allocation, and many more. Most of the areas utilizing AHP involve qualitative decision alternatives where the AHP enables the decision maker to quantify these alternatives (Zahedi, 1986). The AHP has a large variety of applications because of its three primary functions, structuring complexity, measurement, and synthesis; and as a result has been widely researched and analyzed. Since its inception in the 1970s through 1999, the AHP is referenced or studied in over 1000 journal articles and nearly 100 doctoral dissertations (Forman & Gass, 2001).

It may seem unnecessary for high level, experienced decision makers to utilize a methodology to think rationally; however logical thinking is not natural, it is a skill that is developed over time with a great deal of practice (Saaty T. L., 1994). Saaty states that being rational assumes the decision maker is focused on solving the problem, knows enough about the problem to form relationships between criteria and their respective influences, possess or knows where to obtain the knowledge and experience to ensure the previously determined influences are accurate, and have the willingness to compromise (Saaty T. L., 1994). Furthermore, complex problems are typically comprised of many related factors, and so traditional logical thinking "leads to sequences of ideas that are so tangled that their interconnections are not readily discerned" (Saaty T. L., 1994, p. 20). For this reason, one can see how multi-criteria decision-making tools such as AHP are extremely helpful for decision makers. However, while "analytic decision making is of tremendous value…it must be simple and accessible to the lay user, and must have scientific justification of the highest order" (Saaty T. L., 1994, p. 40).

3.3.1.1 PHILOSOPHY, PROCEDURE AND AXIOMS OF THE AHP

The philosophy behind AHP is as follows (Saaty T. L., 1989) (Harker & Vargas, 1987):

Analytic: In holistic decision-making mathematics are not required. It is as simple as selecting the most preferred alternative. However if a decision maker wishes to communicate and defend their choice to others they will likely use a scientific method and logical reasoning. Methods that use mathematics to quantify decisions are by definition analytic.

Hierarchy: The AHP structures complex decision problems into levels that allow the decision maker to focus on smaller, simpler sets of decisions. This is desirable because evidence from human psychology that suggests humans are able to contend with approximately seven items at one time (Miller's Law). Hence, it is imperative that highly complex decision problems be broken into a hierarchy.

Process: Important decisions cannot be made quickly. Decision makers need to have time to gather information, learn from the knowledge obtained, and revise their priorities. The AHP intends to shorten the natural decision making process, not eliminate it.

An effective decision making procedure should be simple to construct, adaptable to both groups and individuals ,intuitive and natural to general thinking, encourage compromise and consensus building, and not require excessive specialization to master and communicate (Saaty T. L., 1994). The AHP encompasses all of these characteristics and is a basic approach to decision making that reveals all interrelationships and tradeoffs. The procedure for the AHP begins with the creation of a decision structure (hierarchy) consisting of the decision goal at the top, the potential alternatives at the bottom and the criteria for which the alternatives are evaluated in the middle. From there the process utilizes a series of pairwise comparisons to prioritize the criteria for ranking and choosing the optimal alternative (Saaty & Vargas, 2001). The mathematical methodology and theory behind paired comparisons is further discussed in section 3.3.1.2, while the following figure illustrates structure of a hierarchy.

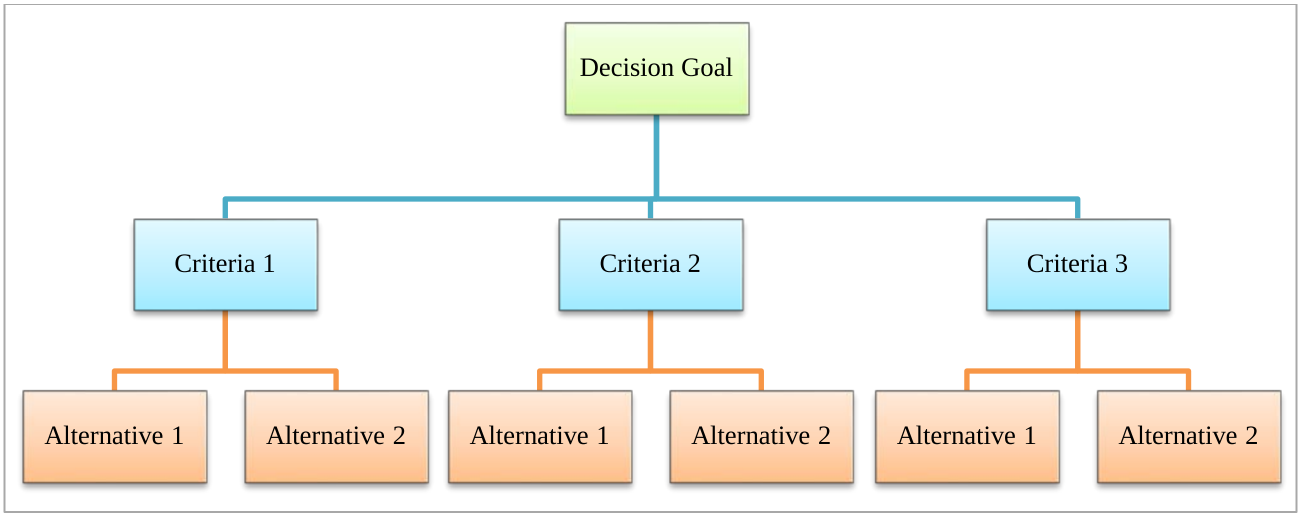

Figure 15: A Three Level Hierarchy: As adapted from (Saaty & Vargas, 2001)

A set of four axioms provide the basis for the AHP methodology. These axioms are as follows (Saaty T. L., 1989) (Forman & Gass, 2001):

Axiom 1 –Reciprocal: This axiom states that for paired comparisons of any two alternatives, $P_C(A,B)$, with respect to any criteria (C), that the ratio scale of how many time more alternative A dominates alternative B is reciprocal, $P_C(B,A) = 1 / P_C(A,B)$. For example if A is three times larger than B then B is one third as large as A.

Axiom 2 – Homogeneity: When comparing alternatives A and B one alternative should never be infinitely larger than the other, under any criteria, $P_C (A, B) \neq \infty$. If alternative A was infinitely larger than alternative B there is no need for a decision tool. Moreover, if the difference between alternatives is too large then errors in comparison judgments will occur. This happens because it is difficult for the human mind to compare widely different attributes. It would be like comparing a grain of sand to an orange and trying to estimate how many orders of magnitude larger the orange is over the grain of sand (Saaty R. W., 1987). Thus, the AHP limits judgments to approximately one order of magnitude for greater consistency and accuracy.

Axiom 3 – Hierarchy Dependence: This axiom simply states that a decision maker can break down a complex decision problem into levels of a hierarchy in which judgments about the criteria in the hierarchy do not depend on lower levels elements.

Axiom 4 – Expectations: The final axiom is inherent and asserts that all criteria and alternatives that influence a decision need to be included in the hierarchy in order to ensure a decision maker's intuition is adequately represented and to ensure the outcome is accurate.

3.3.1.2 MATHEMATICS AND THEORY OF THE AHP

This section discusses the use of the principal eigenvector of a positive pairwise comparison matrix, which is the mathematical methodology and theory behind the AHP. Note that while previous sections have discussed the value of the AHP in making multi-criteria decisions, this research only utilizes the mathematics that determines the weighting value for the items.

The AHP addresses the fundamental issue of decision analysis of how to derive weights for a set of criteria according to their perceived importance (Saaty T. L., 1977). It achieves this by asking the decision maker to make qualitative paired comparisons between criteria, from which quantitative values that represent the weights for each criterion are obtained through liner algebraic methods, specifically eigenvalues and eigenvectors, where "the eigenvector provides the priority ordering and the eigenvalue is a measure of the consistency of judgment" (Saaty T. L., 1980, p. 17). A few important terms concerning linear algebra require discussion before going further into the mathematical theory of the AHP.

Linear algebra is a branch of mathematics that deals with vectors, matrices, vector spaces and systems of linear equations (Cheney & Kincaid, 2009). A matrix is an array of numbers where the horizontal numbers (m) make up the rows, while the vertical numbers (n) make up the columns(i.e. an $m \times n$ matrix).If a matrix has the same number of rows and columns it is said to be a square matrix (i.e. an $n \times n$ matrix). Matrices with only a single column (i.e. an $m \times 1$

matrix) are called vectors. For convenience vectors are often written horizontally such as $\boldsymbol{b} = (b_1, b_2, \ldots, b_n)$ or $\boldsymbol{b} = [b_1, b_2, \ldots, b_n]^T$ (Cheney and Kincaid 2009). Examples of a matrix and column vector are shown in Figure 16.

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \qquad \boldsymbol{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

Figure 16: Matrix *A* and Vector *b*

The indices on an element of the matrix, such as a_{ij}, indicate the number referenced is in row i and column j. Discussion of matrices always follows this notation (Cheney & Kincaid, 2009).

The terms eigenvector and eigenvalue are a specific phenomenon of liner algebra. When a non-zero vector is multiplied by a square matrix and the resulting vector is directly proportional to the original vector (i.e. changes only by a scalar value not in direction), then that vector is an eigenvector and the scalar by which the eigenvector changes is called the eigenvalue (Cheney & Kincaid, 2009). The figure below is an example equation where the eigenvector *(1, 1)* has an eigenvalue of five *(5)*.

$$\begin{bmatrix} 3 & 2 \\ -4 & 9 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 5 \\ 5 \end{bmatrix} = 5 \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

Figure 17: Numerical Example of Eigenvector and Eigenvalue (Cheney & Kincaid, 2009)

The mathematical definition for this phenomenon is as follows (Cheney & Kincaid, 2009):

> *Let **A** be any square matrix, real or complex. A number λ is an **eigenvalue** of **A** if the equation*
>
> $$Ax = \lambda x$$
>
> *is true for some nonzero vector **x**. (Here λ is allowed to be a real or comples number.) The vector **x** is an **eigenvector** associated with the eigenvalues λ. The eigenvector may also be complex.*

Figure 18: Definition of the Eigenvector and Eigenvalue (Cheney & Kincaid, 2009)

Having conveyed the mathematics behind the AHP, discussion about its methodology follows. When considering multiple criteria a decision maker wishes "to insure that the judgments are quantified to an extent which also permits a quantitative interpretation of the judgments among all" of the criteria (Saaty T. L., 1980, p. 22). The AHP accomplishes this by deriving from paired comparisons, a set of weights that are associated with each criterion. For example, let $C_1, C_2, ...C_n$ be the set of criterion, upon which the paired comparisons are made. These paired comparisons denote the quantified judgments between criteria C_i, C_j and are used to populate the square matrix ***A***, where $\boldsymbol{A} = (a_{ij})\ for\ \ i, j = 1, 2, ..., n$ as seen in Figure 19.

$$\boldsymbol{A} = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \end{array}$$

Figure 19: The Form of Matrix *A* (Saaty T. L., 1980)

The entries a_{ij} follow the rules of Axiom 1, Axiom 2, and additionally if C_i is judged to be equally important as C_j, then $a_{ij} = 1$ and $a_{ji} = 1$; and for all cases $a_{ii} = 1$as illustrated by Figure 20.

$$
\boldsymbol{A} = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{array}
\begin{array}{c}
\underline{\begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array}} \\
\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}
\end{array}
$$

Figure 20: The Form of Matrix *A* Showing Rules Followed by the Entries (Saaty T. L., 1980)

The next step is to assign a set of numerical weights $w_1,\ w_2,\ \ldots\ w_n$ to the set of criteria $C_1,\ C_2,\ \ldots C_n$ that reflect the judgments a_{ij}. Beginning with the assumptions that the weights $w_1,\ w_2,\ \ldots\ w_n$ are already known and the numerical judgments from the paired comparisons are exact, then $a_{ij} = \frac{w_i}{w_j}\ for\ \ i, j = 1, 2, \ldots, n\ and\ a_{ik} = a_{ij} \cdot a_{jk}$) (Saaty T. L., 1980). From this ideal situation, Saaty gives the mathematical derivation to arrive at the phenomenon of eigenvectors and eigenvalues, which is demonstrated in Figure 21.

Assuming exact measurements gives the equation:

$$\sum_{j=1}^{n} a_{ij} w_j = nw \qquad i = 1, 2, \ldots, n$$

which is equivalent to the equation:

$$Aw = nw$$

or in matrix form

$$
\boldsymbol{A} = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_m \end{array}
\begin{array}{c}
\underline{\begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array}} \\
\begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_1/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix}
\end{array}
\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}
$$

Figure 21: The Eigenvector and Eigenvalue as Utilized by the AHP: Adapted from (Saaty T. L., 1980)

Given that the previous equation follows the definition of eigenvectors and eigenvalues (Figure 18) and knowing that the pairwise comparisons are based on subjective judgments, the equation $Aw = nw$ becomes $Aw = \lambda_{\max} w$ where $\lambda_{\max}$ is close to *n* and all other eigenvalue are close to zero. Therefore, when the equation $Aw = \lambda_{\max} w$ is solved for the vector *w*, that eigenvector holds the set of numerical weights $w_1,\ w_2,\ ...\ w_n$ for the set of criteria $C_1,\ C_2,\ ...C_n$) (Saaty T. L., 1980).

There are a couple of ways to solve for the eigenvector. The first way is to multiply the entries in a row and take the nth root of that product, for every row after which the results are normalized. Another way to obtain the eigenvector is to square the matrix, sum the elements in each row of the squared matrix and normalize the results. Then take the cube of the matrix, sum the row elements, normalize the results and compare with the results from the squared matrix. The matrix is continually raised to powers until the normalized results for two consecutive calculations converge to some prescribed value of accuracy (Saaty T. L., 1980).

Saaty notes that the deviations in judgments are directly related to the deviation of $\lambda_{\max}$ from *n* and thus the ratio $\dfrac{\lambda_{\max} - n}{n-1}$ is used to measure the consistency of the pairwise comparisons. The AHP calls this ratio the *consistency index* (Saaty T. L., 1980). This measure of consistency is valuable because it is inevitable that inconsistencies will occur. For example, when criteria C_1 is compared to criteria C_2 it is given a value of three times as important ($C_1 = 3C_2$). When criteria C_1 is compared with criteria C_3 it is given a value of five times as important ($C_1 = 5C_3$). If all judgments were consistent then when criteria C_2 is compared with C_3 the resulting algebraic equation ($3C_2 = 5C_3$) is derived from the previous comparisons. This would mean that the value for C_2 would be 5/3 as important ($C_2 = 5/3C_3$) (Saaty T. L., 1994). However, as previously discussed the decision maker would likely assign some other value (e.g. 2 or 3), which results in inconsistencies. This example also demonstrates why the AHP limits judgments to approximately an order of magnitude as discussed in Axiom 2. Limits for judgments come from a scale that is further discussed in the next section.

3.3.1.3 NUMERICAL SCALE FOR PAIRWISE COMPARISONS

The AHP populates a reciprocal matrix using qualitative pairwise comparisons made by a decision maker, based on a scale that represents as many of the distinct feelings people have when making the comparisons (Saaty T. L., 1977). The scale used by the AHP is a one (1) through nine (9) scale making the largest possible difference between two criterion nine times (near an order of magnitude). This one through nine scale is used because of reasons alluded to in Axiom 2 as well as evidence from human psychology that suggests humans are able to contend with approximately seven objects, plus or minus two (7 ± 2), without getting confused (Saaty T. L., 1977). Explanations and definitions for the scale can be seen in Table 13.

Table 13: Scale Utilized by the AHP (Saaty & Vargas, 2001)

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two criteria contribute equally to the objective
2	Weak	
3	Moderate Importance	Experience and judgment slightly favor on criteria over another
4	Moderate Plus	
5	Strong Importance	Experience and judgment strongly favor on criteria over another
6	Strong Plus	
7	Very Strong Importance	An activity is strongly favored and its dominance is demonstrated in practice
8	Very, Very Strong	
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation

In addition to Axiom 2 and psychological evidence, Saaty created a benchmark for the consistency of the one to nine scale. He did so by randomly populating fifty matrices of different orders for several different scales. Then, he averaged the *consistency index* of all fifty matrices for each order as seen in Figure 22 and Table 14.

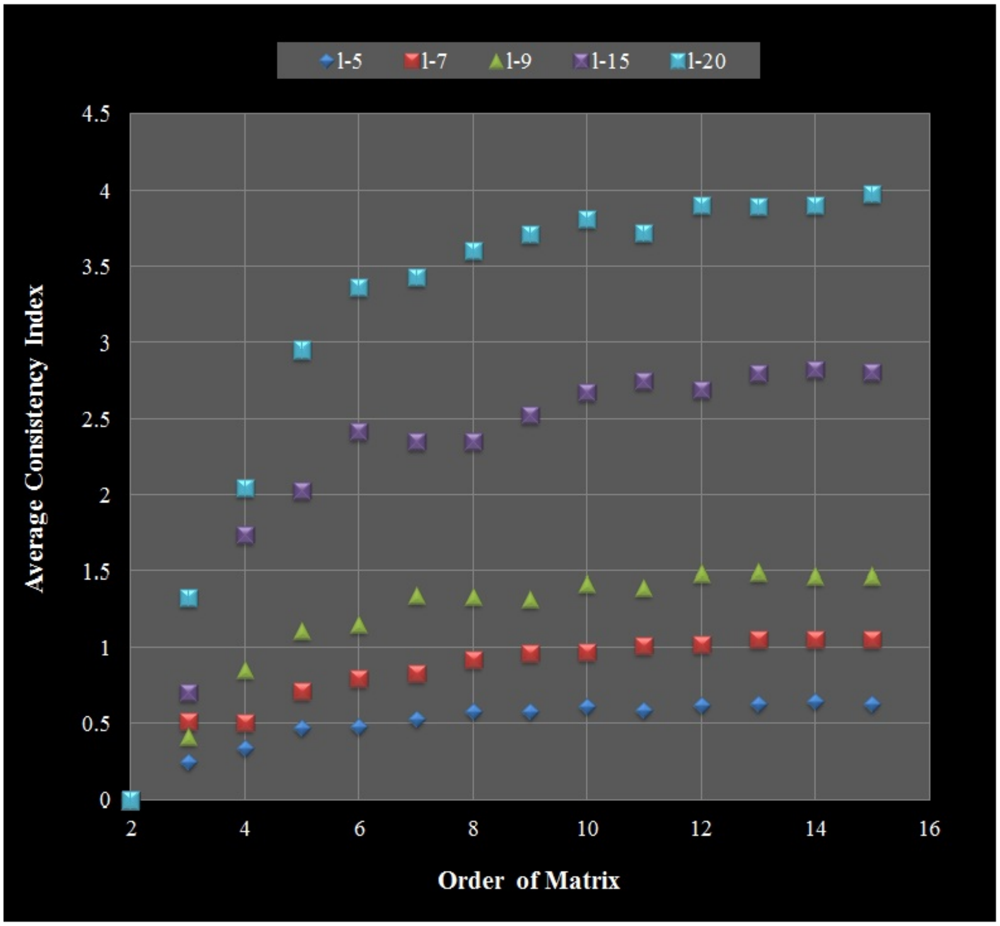

Figure 22: Plot of the Averaged Consistency Index for Each Order: Adapted (Saaty T. L., 1977, p. 248)

Table 14: Averaged Consistency Index for Each Order: Adapted (Saaty T. L., 1977)

Scale	Order of Matrix													
	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 to 5	0	0.244	0.335	0.472	0.479	0.527	0.58	0.577	0.611	0.591	0.623	0.632	0.641	0.629
1 to 7	0	0.515	0.504	0.708	0.798	0.827	0.922	0.961	0.968	1.012	1.019	1.054	1.052	1.052
1 to 9	0	0.416	0.851	1.115	1.15	1.345	1.334	1.315	1.42	1.395	1.482	1.491	1.47	1.466
1 to 15	0	0.705	1.733	2.024	2.416	2.349	2.351	2.525	2.674	2.749	2.693	2.804	2.827	2.806
1 to 20	0	1.326	2.044	2.948	3.354	3.428	3.598	3.709	3.807	3.719	3.899	3.888	3.895	3.971

Furthermore, two additional studies were conducted for the one through nine scale. Saaty and colleagues generated and randomly populated a large numbers of matrices (100 and 500) of varying orders, and developed the *random index,* as shown in Table 15 (Saaty T. L., 1980).

Table 15: The Random Index (Saaty T. L., 1980)

Order of Matrix	Random Index
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

The *random index* is a benchmark that enables decision makers to evaluate the level of consistency for their particular situation. In other words, it indicates as a ratio how different the judgments are from random responses (Saaty T. L., 1989). This comparison is done by dividing the *consistency index* of a given matrix by the *random index* to obtain the *consistency ratio*

$\left(CR = \dfrac{CI}{RI} \right)$, which should be a value ≤ 0.10 to be considered acceptable (Saaty T. L., 1980). It should be noted that while Saaty test matrices of orders higher than ten, he states that the process described in this section is mainly useful when $n \leq 10$ (Saaty T. L., 1980).

3.3.1.4 An Example of the AHP used for Determining Weighting Values

This section provides a systematic example of how the AHP will be used in this research. The example assumes that there are four criteria, C_1, C_2, C_3, and C_4 being considered. The first step is to setup the pairwise reciprocal matrix.

$$\mathbf{A} = \begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \\ C_4 \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & C_3 & C_4 \end{array} \\ \begin{bmatrix} 1 & a_{12} & a_{13} & a_{14} \\ 1/a_{12} & 1 & a_{23} & a_{24} \\ 1/a_{13} & 1/a_{23} & 1 & a_{34} \\ 1/a_{14} & 1/a_{24} & 1/a_{34} & 1 \end{bmatrix} \end{array}$$

Next, the decision maker makes judgments about the relative importance between two criteria using the one to nine scale, and fills in the matrix. Note that since reciprocal values are used the number of comparisons needed is $\dfrac{n(n-1)}{2}$ not n^2 (Saaty T. L., 1989). The decision maker makes the following judgments:

C_1 vs. $C_2 \rightarrow 2$ C_1 vs. $C_3 \rightarrow 1/4$ C_1 vs. $C_4 \rightarrow 4$

C_2 vs. $C_3 \rightarrow 1/8$ C_2 vs. $C_4 \rightarrow 1/2$ C_3 vs. $C_4 \rightarrow 6$

Therefore the resulting matrix and linear equation is:

$$\begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \\ C_4 \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & C_3 & C_4 \end{array} \\ \begin{bmatrix} 1 & 2 & 1/4 & 4 \\ 1/2 & 1 & 1/8 & 1/2 \\ 4 & 8 & 1 & 8 \\ 1/4 & 2 & 1/8 & 1 \end{bmatrix} \end{array} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \lambda_{\max} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}$$

As previously stated there are a couple of ways to determine the eigenvector. The one used for this example will be to take the product of each row, take the nth root of that product and then normalize the results. This method is not as tedious and is a very good approximation of the method that continually raises the matrix to powers until the results converge (Saaty T. L., 1980).

$$\begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \\ C_4 \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & C_3 & C_4 \end{array} \\ \begin{bmatrix} 1 & 2 & 1/4 & 4 \\ 1/2 & 1 & 1/8 & 1/2 \\ 4 & 8 & 1 & 8 \\ 1/4 & 2 & 1/8 & 1 \end{bmatrix} \end{array} \quad \begin{array}{c} \text{Row Product} \\ \begin{bmatrix} 2 \\ 0.031 \\ 256 \\ 0.063 \end{bmatrix} \end{array} \quad \begin{array}{c} \sqrt[4]{\text{Row Product}} \\ \begin{bmatrix} 1.189 \\ 0.420 \\ 4.00 \\ 0.50 \end{bmatrix} \end{array} \quad \begin{array}{c} \text{Normalized Eigenvector} \\ \begin{bmatrix} 0.195 \\ 0.069 \\ 0.655 \\ 0.082 \end{bmatrix} \end{array}$$

After finding and normalizing the eigenvector, the decision maker needs to calculate the maximum eigenvalue $(\lambda_{\max})$. The original for calculating $(\lambda_{\max})$ is to multiply every element in a row by the corresponding element in the normalized eigenvector, taking the sum of the products and dividing that sum by the element in the eigenvector that is of the same row as represented by the following formula (Saaty T. L., 1977).

$$\lambda_{\max} = \sum_{j=1}^{n} a_{ij} \left(w_j / w_i \right)$$

A second method for calculating the maximum eigenvalue $(\lambda_{\max})$ is to sum the elements in every column to form a row vector, then multiplying the new row vector by the normalized eigenvector as represented by the following formulas (Saaty R. W., 1987).

$$\sum_{j=1}^{n} a_{ij} w_j = \lambda_{\max} w_i$$

$$and$$

$$\sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} w_j = \sum_{j=1}^{n} \left(\sum_{i=1}^{n} a_{ij} \right) w_j = \sum_{i=1}^{n} \lambda_{\max} w_i = \lambda_{\max}$$

$$\begin{array}{lcccc} & C_1 & C_2 & C_3 & C_4 \\ \hline Sum\ of\ \ Columns\ (New\ Row\ Vector): & [5.75 & 13 & 1.5 & 13.5] \end{array}$$

$$\begin{bmatrix} 5.75 & 13 & 1.5 & 13.5 \end{bmatrix} \times \begin{bmatrix} 0.195 \\ 0.069 \\ 0.655 \\ 0.082 \end{bmatrix} = 4.101 = \lambda_{\max}$$

This technique for calculating $\lambda_{\max}$ is the method that will be utilized by this research.

Discussion in previous sections noted that this value should be approximately the number of criteria being considered (*n*); the more consistent the judgments the closer the values will be to being the same and close to *n*. Once the maximum eigenvalue $(\lambda_{\max})$ is found the decision maker then calculates the aforementioned *consistency index* using the formula $\frac{\lambda_{\max} - n}{n-1}$. This value is then divided by the *random index* (see Table 15) for the order of the matrix to obtain the *consistency ratio*. For the given example the *consistency ratio* is:

$$Consistency\ Index = \frac{4.101 - 4}{4 - 1} = 0.0337\ ;\ \ Cosistency\ Ratio = \frac{0.0337}{0.90} = 0.037$$

In this example, the highest *consistency ratio* is 0.037, which indicates that 3.7% of the judgments are not significantly different from random responses. However, since this value is less than 0.10 the level of consistency in the paired comparison judgments is satisfactory and the normalized eigenvector contains the set of weights that corresponds to the criteria being considered. This example demonstrates how the AHP will be used to determine the relative weighting factors for the respective items in bridge management components.

3.3.2 SEEKING PROFESSIONAL AND EXPERT OPINIONS TO IDENTIFY EACH ITEM'S RELATIVE IMPORTANCE AS REPRESENTED BY WEIGHTING FACTORS FOR EACH COMPONENT

Once the items for each component are identified through the first survey as discussed earlier, the respondents to that survey will be contacted again to administer the AHP survey. For this, they will be sent an electronic document (an Excel spreadsheet that contains drop down boxes), accompanied by instructions, to provide pairwise comparisons as required by AHP. The pairwise comparisons will require the participant to make a judgment between two items about which item is more important, along with the degree of that importance. A more in depth discussion on how participants will make the comparisons and fill in the spreadsheet, along with figures for illustration, are found in Appendices E and F.

Upon completion, the respondents' results will be used to generate an overall matrix. This will be done by taking the geometric mean of each input cell from each respondent. For example, a given cell value for respondent one is represented by (a_{ij}^1) and for respondent two as (a_{ij}^2), and so forth. Let us assume that there are four respondents and for cell $a_{ij} = a_{12}$ assigned the following values $a_{12}^1 = 5$; $a_{12}^2 = 6$; $a_{12}^3 = 7$; $a_{12}^4 = 5$. Therefore geometric mean for cell $a_{ij} = a_{12}$ in the group matrix is $\left(5 \times 6 \times 7 \times 5\right)^{1/4} = 5.69$. The geometric mean is a valid way of combining the input from several respondents to obtain a reciprocal matrix that is a good representation of the judgments of the group (Saaty & Aczel, 1983) (Saaty T. L., 1989). The matrix constructed using the geometric mean is what will be used to determine the final weighting factors for the respective items of the bridge management components. In addition, the *consistency index (CI)* for the group judgments is determined using the formula $\frac{\lambda_{\max} - n}{n}$ and then *consistency ratio (CR)* of the entire group will be calculated by $\left(CR = \frac{CI}{RI} \right)$, and should be less than 0.10 (Saaty T. L., 1989).

CHAPTER 4: RESULTS

In an attempt to answer the research questions presented in Section 1.5, a two part survey of expert opinions was conducted to (i) identify the appropriate items that make up each bridge management component and (ii) determine the relative importance of those items as well as the bridge management components as represented by weighting factors. This chapter presents the results of both parts of the survey.

4.1 OUTCOME OF SURVEY (PART 1) – FINALIZING ITEMS FOR EACH COMPONENT

A solicitation email along with the first part of the survey (see Appendices B, C, and D) were sent to nearly 300 experts and professionals in the field of bridge management and maintenance, which included personnel from local, State, and Federal agencies as well as consultants and academics. The total number of respondents was 47, of which 32 were from 29 different State transportation agencies. While this response rate was significantly less than what was desired (approximately 16%), it was presumed sufficient to provide a meaningful sample size concerning State transportation agencies (58% of states represented), since the immediate interest and primary beneficiaries of this research are State bridge management and maintenance engineers. Literature on response rates suggests that a typical response rate when surveying executives averages about 32% with the inter-quartile range being 20% to 46% (Cycyota & Harrison, 2006).

As discussed in Chapter 3, the questionnaire presented participants with three options; check an “agree” box, a “disagree” box, or a “disagree and move” to a different component box. Upon receiving results from all 47 participates, the responses were combined and percentage ratios were calculated for all three options. An item was considered validated under its component if the ratio of participants who checked "agree" boxes to the total number of participants was greater than the ratios for respondents that checked "disagree" and "disagree and move" boxes. However, an item was removed completely or moved it to a different component if one of the other respective ratios governed. All of the proposed items presented in Chapter 3 were verified by having a greater (in many cases significantly greater) percentage ratio of "agree" responses than "disagree", or "disagree and move" response options. However, there were four items deemed "debatable items"; having a percentage ratio of "agree" responses noticeably lower than the other items.

The results of the first part of the survey are summarized in the following Tables (16 through 21), and show the numbers, resulting ratios (expressed as a percentage), and how the "disagree" and move" recommendation for each item is distributed amongst the other components; "debatable" items are denoted with an asterisk (*). The reader is referred to Section 5.2.3 for further discussion, in a general sense, about the relationship between "debatable items" and possible participant confusion, with detailed commentary on the Posting item. Not every participant responded or made a recommendation for every item under each component as was intended by the researcher; therefore, not every item has 47 responses.

Table 16: Results for Structural Condition Component – Numbers and Ratios

Structural Condition Item	Total Number of Responses	Agree		Disagree		Move	
Superstructure	47	46	98%	1	2%	0	0%
Posting*	44	28	64%	6	14%	10	23%
Substructure	47	46	98%	1	2%	0	0%
Deck/Slab	45	45	100%	0	0%	0	0%
Inventory Rating	44	33	75%	4	9%	7	16%
Bearings	46	41	89%	3	7%	2	4%
Joints	46	36	78%	6	13%	4	9%
Protective Systems	44	33	75%	8	18%	3	7%
Bridge Railing*	42	24	57%	10	24%	8	19%
Approach Slabs*	46	23	50%	19	41%	4	9%

Table 17: Results for Structural Condition Component – Distribution of Recommendations

Structural Condition Item	Move	Move to Impact on Public Component	Move to Hazard Resistance Component	Move to Preservation / Maintenance Component
Superstructure	0			
Posting*	10	10		
Substructure	0			
Deck/Slab	0			
Inventory Rating	7	7		
Bearings	2	1		1
Joints	4	1	1	2
Protective Systems	3		1	2
Bridge Railing*	8	6	1	1
Approach Slabs*	4	3	1	

Table 18: Results for Impact on Public Component – Numbers and Ratios

Impact on Public Item	Total Number of Responses	Agree		Disagree		Move	
Posting	46	44	96%	2	4%	0	0%
Approach Roadway Alignment	47	43	91%	3	6%	1	2%
ADT and ADTT	47	46	98%	1	2%	0	0%
Underclearances	46	44	96%	2	4%	0	0%
Deck Geometry	43	41	95%	2	5%	0	0%
Detour Length	47	45	96%	2	4%	0	0%
Bridge Railing	44	35	80%	4	9%	5	11%
STRAHNET Designation[1]*	45	25	56%	17	38%	3	7%

[1]Two (2) of the participants recommended moving this items but did not specify a component.

Table 19: Results for Impact on Public Component – Distribution of Recommendations

Impact on Public Item	Move	Move to Structural Condition Component	Move to Hazard Resistance Component	Move to Preservation / Maintenance Component
Posting	0			
Approach Roadway Alignment	1		1	
ADT and ADTT	0			
Underclearances	0			
Deck Geometry	0			
Detour Length	0			
Bridge Railing	5	2	3	
STRAHNET Designation[1]*	3	1		

[1]Two (2) of the participants recommended moving this items but did not specify a component.

Table 20: Results for Hazard Resistance Component – Numbers and Ratios

Hazard Resistance Item	Total Number of Responses	Agree		Disagree		Move	
Scour Critical	45	44	98%	1	2%	0	0%
Underclearances	43	35	81%	6	14%	2	5%
Channel and Channel Protection	45	40	89%	3	7%	2	4%
Waterway Adequacy	45	38	84%	5	11%	2	4%
Structure Type	44	35	80%	7	16%	2	5%
Seismic Design	45	42	93%	3	7%	0	0%
Seismic Zone	46	43	93%	3	7%	0	0%

Table 21: Results for Hazard Resistance Component– Distribution of Recommendations

Hazard Resistance Item	Move	Move to Structural Condition Component	Move to Impact on Public Component	Move to Preservation / Maintenance Components
Scour Critical	0			
Underclearances	2		2	
Channel and Channel Protection	2	1		1
Waterway Adequacy	2		2	
Structure Type	2	2		
Seismic Design	0			
Seismic Zone	0			

The preceding tables show that the "agree" ratios for every item was greater that the "disagree", or the "disagree and move" ratio, and therefore the listed items are the same as the original proposed items. Additionally the questionnaire provided participants with space to provide suggestions for additional, possibly overlooked, items as well as any other comments given. The following Tables list the items suggested by the participants.

Table 22: Suggested Items for Structural Condition Component

Suggested Item	Participant Number
Type of Repair	4
Culvert	5 & 17
Protective System for Superstructure	8
Turndown or End Diaphragms	11
Age / Year Built	13 & 32

NBIS Item 67: Structural Evaluation	14 & 32
Operating Rating	17
Steel Coating	21
Service Life	24
Scheduled Improvements	24
Wearing Surface	28
Foundation Types	29
Classified as Structurally Deficient	32

Table 23: Suggested Items for Impact on Public Component

Suggested Item	Participant Number
Capacity	2
Operating Rating	3
School Bus Route	4 & 25
Bridge Roadway Width	5
High Accident Location	7
Waterway Adequacy	21
Joints	23
Pedestrian Access (i.e. ADA Compliance)	24
Utilities (i.e. Illumination and ITS)	24
Overclearance	27
National Highway System	28 & 30
Traffic Signs	29
Classified as Functionally Obsolete	32
Age / Year Built	32
Deck Condition	33

Table 24: Suggested Items for Hazard Resistance Component

Suggested Item	Participant Number
Ship Impact / Vessel Collision	3 & 24
Storm Surge	3
Unknown Foundation	4
Fracture Critical Structure	4 & 21 & 30
Bridge Railing	16
Anti-Terrorism Design	24
Blank Item	27
Environment	29
Structural Material Type	30

There were several comments that accompanied the check boxes and the items listed in the previous tables. The most prominent suggestion is associated with the creation of a fourth bridge management component, which would encompass items that are typically associated with bridge preservation and maintenance. This concept was specifically stated, or alluded to in some form, by several participants. Refer to Section 5.2.1 for further discussion concerning a fourth component and other recommended modifications. Note that a complete list of 34 participants' comments (not all participants had comments or suggestions) is located in Appendix G.

4.2 Outcome of Survey (Part 2) – Identifying Each Item's Relative Importance

Based on the results from the first part of the survey ("agree" ratios were greater than the "disagree", or the "disagree and move" ratios), all of the items that were originally proposed for each component (as listed in Table 25) were kept and moved forward to the second part of the survey to identify their relative weights, however no items were added.

Table 25: Finalized Items for Each Component

Structural Condition Component	Impact on Public Component	Hazard Resistance Component
Superstructure	Posting	Scour Critical
Posting	Approach Roadway Alignment	Underclearances
Substructure	ADT and ADTT	Channel and Channel Protection
Deck/Slab	Underclearances	Waterway Adequacy
Inventory Rating	Deck Geometry	Structure Type
Bearings	Detour Length	Seismic Design
Joints	Bridge Railing	Seismic Zone
Protective Systems	STRAHNET Designation[1]	
Bridge Railing		
Approach Slabs		

As stated in Section 3.3.2, these finalized items were included in a spreadsheet application (see appendices E and F), which allowed each participant to individually make pairwise comparisons using his/her judgment, with the ultimate purpose of determining each item's relative importance. Only the 47 participants that responded to the first part of the survey received the spreadsheet application. Similar to the first part of the survey, the response rate was less than desired. Of the 47 participants, only 27 contributed to the second part of the survey.

The overall group results, determined using the geometric mean as discussed in Section 3.3.2, are shown in Tables 26 through 29.

Table 26: Relative Importance of Structural Condition Items

Items	Relative Importance
Superstructure	0.22
Posting*	0.19
Substructure	0.18
Deck/Slab	0.10
Inventory Rating	0.08
Bearings	0.07
Joints	0.06
Protective Systems	0.04
Bridge Railing*	0.04
Approach Slabs*	0.02

Table 27: Relative Importance of Impact on Public Items

Items	Relative Importance
Posting	0.30
Approach Roadway Alignment	0.12
ADT and ADTT	0.12
Underclearances	0.11
Deck Geometry	0.10
Detour Length	0.09
Bridge Railing	0.09
STRAHNET Designation*	0.07

Table 28: Relative Importance of Hazard Resistance Items

Items	Relative Importance
Scour Critical	0.31
Underclearances	0.16
Channel and Channel Protection	0.14
Waterway Adequacy	0.12
Structure Type	0.10
Seismic Design	0.10
Seismic Zone	0.07

Table 29: Relative Importance of Bridge Management Components

Components	Relative Importance
Structural Condition	0.56
Impact on Public	0.25
Hazard Resistance	0.19

An important aspect of the AHP is to detect how consistent participants' judgments are when making paired comparisons. In order to consider judgments as being consistent, the consistency ratio needs to be 0.10 or less as previously stated in Section 3.3.1.3. While the consistency ratios for the group were less than 0.10 for each component, the individual consistency ratios were highly variable as exhibited in subsequent table.

Table 30: Consistency Ratios

Component	**Group Consistency Ratio**	**Maximum Individual Consistency Ratio**	**Minimum Individual Consistency Ratio**	**Average Individual Consistency Ratio**
Structural Condition	0.0127	0.48	0.03	0.13
Impact on Public	0.0471	1.05	0.05	0.32
Hazard Resistance	0.0092	0.40	0.01	0.14
All Components	0.0000	0.48	0.00	0.10

After an extensive review, it was determined to use the judgments of all participants to calculate the group response, even though some individual participant consistency ratios' were above the recommended value of 0.10. This method was concluded to be reasonable because, (i) the geometric mean utilized to compute the overall group results tends to compensate for the inconsistencies of individual judgments, and (ii) the primary objective sought was the true opinions of experts (as a whole group), even if that opinion is inconsistent in certain cases. It is important to note that Figueroa (2010) justifies this approach in performing AHP for the Virginia Department of Transportation to identify the weights of different asset items for maintenance performance evaluation decisions.

As previously mentioned the group consistency ratio is within the acceptable limits as suggested by AHP literature, however, future research as discussed in Section 5.5, could investigate revising the judgments so that the individual consistency ratios' are reduced to below 10% and the results compared to the results of this project.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This chapter provides the conclusions derived from the results presented in the previous chapter and ensuing recommendations. First, a summary of the research is presented, followed by the value resulting from participant responses and comments, along with their potential effects on the results and how they relate to potential confusion among the participants. Then the researcher provides prospective users with potential implementation and utilization strategies of the finalized results. After that, the contribution to the body of knowledge along with commentary on comments received regarding the purpose and merits of this research are presented. This chapter concludes with a discussion on possible future research related to this study.

5.1 SUMMARY OF THE RESEARCH

Ensuring the optimal allocation of resources between competing bridges in a transportation network is difficult; particularly when available resources (specifically funding) to address preservation and improvement needs are limited, the bridges are aging and continue to deteriorate and there is an ever greater demand on this essential and expensive component of the transportation system.

BMSs are a commonly utilized tool that aids managers and decision makers in establishing methods for optimizing available resources and determining how to distribute funds between competing bridges. Recently, *NCHRP Synthesis 397 Bridge Management Systems for Transportation Agency Decision Making* investigated how transportation agencies are using BMSs and the status of bridge management practices (Markow & Hyman, 2009). The report identified shortcomings and drawbacks with bridge management practices that base decisions solely on single value assessments such as Pontis' Bridge Health Index or the NBIS Sufficiency Rating. Given the criticisms found in this report and other literature on bridge management, it is evident that there is a need to pursue and develop alternative bridge management practices and systems.

The overall purpose of this research was to investigate the concept of isolating items used to make up a single rating or index in commonly utilized BMSs (i.e. Sufficiency Rating and Bridge Health Index) in an effort to categorize them into different, serviceable bridge management components (i.e. Structural Condition, Impact on Public and Hazard Resistance).

Having isolated bridge management components allows for a straightforward approach in detecting differences among structures, which in turn may help decision-makers in developing BMSs and conducting tradeoff analysis for prioritizing work and determining inspection cycles. Each bridge management component has a distinct objective as follows:

- <u>Structural Condition</u> - accurately access the structural adequacy of a bridge.
- <u>Impact on Public</u> - evaluate how bridge attributes affect the traveling public.
- <u>Hazard Resistance</u> - evaluate how bridge attributes and external factors affect the vulnerability of a bridge concerning the probability of an extreme event as well as the probability of failure during that event.

The specific objectives of this research were (i) to identify the appropriate items that make up each of the aforementioned components and (ii) to determine the relative importance of those items as represented by weighting factors. In addition to the primary objective previously mentioned, this research will also determine the relative importance of the three components and assign associated weighting factors. To achieve these objectives, the researcher conducted two surveys seeking input from key bridge management personnel from State DOTs, the FHWA and other industry professionals and experts. The first survey identified the appropriate items while the second survey determined the relative importance of those items using a mathematical method entitled the Analytic Hierarchy Process (AHP).

In summary, there is a general lack of confidence in the field of bridge management about the current bridge management methods. With this sentiment, bridge managers, transportation agencies, and private companies are attempting to develop BMSs and practices customized to their particular needs. The primary contribution of this research is to provide managers and decision makers with effective bridge management components that facilitate the recognition of variations in bridge attributes. Once the bridge management components are established (by determining the items that make up the components and their relative weights), transportation agencies may utilize them in a variety of ways to develop customized BMSs and tradeoff analyses that complement their current bridge management practices; which in turn may better illustrate the performance of bridges on their system. Based on the two part survey results, the established bridge management components, related items and relative weighting factors are shown in Table 31:

Table 31: Combined Final Survey Results

Structural Condition Component		Impact on Public Component		Hazard Resistance Component	
Items	**Relative Importance**	**Items**	**Relative Importance**	**Items**	**Relative Importance**
Superstructure	22%	Posting	30%	Scour Critical	31%
Posting*	19%	Approach Roadway Alignment	12%	Underclearances	16%
Substructure	18%	ADT and ADTT	12%	Channel and Channel Protection	14%
Deck/Slab	10%	Underclearances	11%	Waterway Adequacy	12%
Inventory Rating	8%	Deck Geometry	10%	Structure Type	10%
Bearings	7%	Detour Length	9%	Seismic Design	10%
Joints	6%	Bridge Railing	9%	Seismic Zone	7%
Protective Systems	4%	STRAHNET Designation*	7%		
Bridge Railing*	4%				
Approach Slabs*	2%				

5.2 VALUE DERIVED FROM PARTICIPANT COMMENTS THAT AFFECT FINDINGS

As briefly introduced in Section 4.1, the most prominent participant remarks dealt with quantifying preservation and maintenance demands. The following section further expands on the concept of adding a fourth bridge management component for bridge preservation and maintenance. After that there is commentary regarding additional modifications to the Structural Condition and Hazard Resistance Components, along with the potential effects of possible confusion amongst participants on the results. This section concludes with discussion about the subsequent modifications, based on participant comments and recommendations, made to the components, items and, relative importance shown in Table 31.

5.2.1 DEVELOPMENT OF PRESERVATION AND MAINTENANCE COMPONENT AND MODIFICATIONS TO THE STRUCTURAL CONDITION COMPONENT

As shown in Table 32, there were several participants with comments related to the modification of the Structural Condition Component.

Table 32: Participant Comments Pertaining to the Structural Condition Component

Participant 1	• *<u>Protective Systems:</u>* [Comment] Paint, deck protection systems, cathodic protection systems etc., are not a structural (load carrying) component. They do however affect the durability (useful life) of a bridge. Suggest moving to Hazard Resistance with the environmental degradation the hazard. • *<u>Approach Slabs:</u>* [Move to] Impact on Public. Again, approach slabs are not a structural component but help move the "bump" away from the bridge and may provide temporary access should the approach embankment be lost during a flood or earthquake. • *<u>Bridge Railing:</u>* [Move to] Impact on Public. Not a structural component but safety feature used to protect the public. • *<u>Joints:</u>* [Comment] Not a structural component. Not sure Hazard?
Participant 6	• *<u>Protective Systems:</u>* [Add new] preservation component [and move to said component] • *<u>Joints:</u>* [Add new] Preservation component [and move to said component] • *<u>Structural Condition:</u>* [Comment] Suggest creating a 4th component for preservation ... include paint, joints, channel protection, wearing surface, cathodic protection, etc.
Participant 10	• *<u>Structural Condition:</u>* [Comment] Need another category for "Maintenance Needs" for some items. Deck should be included in this category also.
Participant 14	• *<u>Structural Condition:</u>* [Comment] Slabs more greatly influence ride-ability, comfort etc. Only a total deck failure would affect structural capacity. Approach slabs are not part of the bridge and certainly not structural.
Participant 15	• *<u>Impact on Public:</u>* [Comment] Bridge Railing also shows up in the Structural Condition Components
Participant 16	• *<u>Hazard Resistance:</u>* [Add Item] Bridge Railing
Participant 18	• *<u>Structural Condition:</u>* [Comment] Superstructure should be divided out between the different types, i.e., Steel, Pre-stressed Concrete Girders, PT /PS Spliced Concrete girders.

Participant 19	• *<u>Deck / Slab:</u>* [Comment] Deck & Slabs should be separate. • *<u>Structural Condition:</u>* [Add Item] Concrete Deck Soffit: This condition is independent of the top surface. Concrete Deck's primary function amounts to tracking deterioration. Timber & steel decks are a structural evaluation.
Participant 21	• *<u>Structural Condition:</u>* [Comment] If you are only interested in evaluating the structural integrity of the bridge, then I believe all of the identified items are essential in the structural evaluation process. However, if you're interested in evaluating the preservation replacement and improvement needs, then you will need information on all bridge elements. • *<u>Bridge Railing:</u>* [Comment] Applies from safety perspective
Participant 22	• *<u>Structural Condition:</u>* [Comment] We need to move away from structural deficiency or adequacy. Need to define state of good repair, or good fair poor.
Participant 23	• *<u>Structural Condition:</u>* [Comment] Would remove joints & rails unless it was more specific, e.g., deck condition within the development length of the steel from the joint/railing? Otherwise, except for impact to the railing, these are mostly irrelevant to the load path, and therefore more maintenance issues than structural issues per se.
Participant 24	• *<u>Structural Condition:</u>* [Add Item] Remaining Bridge Service Life, Proposed or Scheduled Improvements
Participant 26	• *<u>Structural Condition:</u>* [Comment] Joints, bearings and approach slabs might be better defined or split upon what ails them. If it is a riding issue across a joint, it could be under Impact on Public. … You would not replace the bridge if the joint(s) were bad, you would replace/repair the joint.
Participant 34	• *<u>Superstructure:</u>* [Comment] Differentiate more I think • *<u>Substructure:</u>* [Comment] Differentiate more I think

Four of the original proposed items (Joints, Protective Systems, Bridge Railing and Approach Slabs) appear frequently in the participant comments as to how they pertain more to preservation and maintenance than to structural adequacy and safety of the traveling public. Furthermore, these four items rated the lowest in terms of importance when compared to other items under the Structural Condition Component as seen in Table 26. Additionally, the survey results present in Table 16 classify the Approach Slabs Bridge Railing items as "debatable items", which further justifies and reflects the participant comments in the previous table. Therefore, due to the survey results and the common theme, as established throughout the listed comments, of taking into consideration preservation and maintenance demands, it is concluded that a fourth bridge management component for preservation and maintenance be developed. The Preservation and Maintenance Component will include Joints, Protective Systems, Bridge Railing and Approach Slabs as items, and subsequently remove these items from the Structural Condition Component.

Another conclusion derived from the listed comments is that the Deck/Slab item, in some instances, may correspond to both the Structural Condition Component and the suggested Preservation and Maintenance Component. For instance, the superstructure design may account for the load carrying capacity of a cast-in-place (CIP) concrete deck, and thus deficiencies in the deck could potentially compromise its strength and the overall structural capacity of the bridge. However, if the structural contribution of the CIP concrete deck is not accounted for in the design the deck may function more as a maintenance item. The previous discussion is noteworthy because based on the 2010 NBI statistics 86% of the total deck areas of the nation's bridges are comprised of CIP concrete decks (FHWA, 2010). Additionally, a large majority of bridge superstructures are constructed using multi-beam girders (steel and concrete) as seen in Table 33.

Table 33: Top Ten Most Common Bridge Types (FHWA, 2010)

Bridge Type	Number of Bridges	Percentage of Total[1]	Percentage of Total[2]
Stringer/Multi-Beam or Girder	249,165	41%	53%
Culvert	130,846	22%	-
Slab	80,333	13%	17%
Box Beam or Girders (Multiple)	49,916	8%	11%
Tee Beam	35,801	6%	8%
Channel Beam	14,382	2%	3%
Truss-Thru	10,957	2%	2%
Box Beam or Girders (Single or Spread)	8,812	1%	2%
Girder & Floorbeam System	6,884	1%	1%
Arch-Deck	6,860	1%	1%
Total Number of Bridges	604,493		
Number of Bridges - Top 10 Types	593,956	98%	

Number of Bridge Excluding Culverts	473,647		78%

[1]Percentage based on the total number of bridges (604,493)
[2]Percentage based on the total number of bridges excluding the culverts (473,647)

An additional suggestion made by participants 19 and 34 is to separate the Deck/Slab item two separate items. The researcher concurs with this comment because by definition, a Slab element in a Concrete Slab Bridge (see Table 33) is always going to be the superstructure as well as the driving surface and therefore the condition of the Slab will always directly affect a bridge's structural capacity whereas a Deck may not as mentioned earlier. Based on the preceding discussions it is concluded that the Deck/Slab item be broken down and the Slab be included with the Superstructure item, resulting in two new items, (i) Deck and (ii) Superstructure / Slab. The Deck item is included in both the Structural Condition and the newly developed Preservation and Maintenance Component while the Superstructure / Slab item is only listed under the Structural Condition Component as illustrated in Table 36 in Section 5.2.4.

Finally, there were comments noting that the Superstructure and Substructure items could be further broken down into multiple items, analogous to the CoRe elements as discussed in Sections 2.2 and 2.3.2.1. While the researcher appreciates and agrees with this logic, the primary purpose of this research is to determine the items that structure bridge management components and their relative weights in a general sense. In other words, the combination of material and construction types for superstructures and substructures are very diverse, and thus using their individual elements as items would complicate the Structural Condition Component, rendering it not applicable or uniform to an entire network set of bridges. In that sense, the Superstructure and Substructure items are sufficient for assessing the structural adequacy of bridges across an entire transportation network. However, bridge managers in customizing the bridge management components, as determined by this research, to fit their specific needs, may consider breaking down the Superstructure and Substructure items.

5.2.2 MODIFICATIONS TO HAZARD RESISTANCE COMPONENT

Several participants provided additional comments resembling those mentioned in Section 5.2.1, suggesting modification to the items that reside under the Hazard Resistance Component as listed in Table 34.

Table 34: Participant Comments Pertaining to the Hazard Resistance Component

Participant 2	• *Hazard Resistance:* [Comment] Seismic zone and design are listed as indicators of a potential seismic risk. These indicators are vague (Design) or crude (Seismic zone) approximations of the potential vulnerability.
Participant 3	• *Hazard Resistance:* [Add Item] Vulnerability to ship impact and vulnerability to storm surge
Participant 4	• *Hazard Resistance:* [Add Item] Fracture Critical
Participant 8	• *Hazard Resistance:* [Comment] It might be clearer if the seismic design was moved to the Structural Condition section. In major rehabilitations, we always try to address any seismic issues.
Participant 14	• *Hazard Resistance:* [Comment] Scour critical channel and channel protection and waterway adequacy go hand in hand and could be one item.
Participant 18	• *Waterway Adequacy:* [Comment] I would think that this information could be captured under the channel and channel protection category.
Participant 21	• *Hazard Resistance:* [Add Item] Fracture Critical and fatigue prone details should be considered
Participant 23	• *Hazard Resistance:* [Comment] Seismic design & seismic zone should be combined into "seismic adequacy." Including structure type really implies some sort of unlisted hazard, which has greater impact on certain structure types. Better to look at the hazard and have a resistance assessment for that. Underclearance and channel protection should be related to some sort of hazard, e.g., collision hazard.
Participant 24	• *Hazard Resistance:* [Add Item] Vessel Collision Protection
Participant 26	• *Hazard Resistance:* [Comment] Underclearances - prorated on how restrictive / probability of impact / consequences. Seismic Design should trump seismic zone - if a bridge is designed to handle zone, then OK.
Participant 30	• *Hazard Resistance:* [Add Item] Fracture criticality

The items Seismic Zone and Seismic Design were isolated in an attempt to take into account the probability of an event (Seismic Zone) and the probability of failure during that event (Seismic Design). Participants 2, 8, 23 and 26 commented on these items, and suggested combining them into a single item labeled “Seismic Adequacy”. The researcher considers this reasonable because the Seismic Zone is fixed and thus the only variable is whether the bridge is properly designed for a seismic event corresponding to its seismic zone (Seismic Design); and if it has, then as stated by participant 26, the overall seismic adequacy of the structure is acceptable. Combining these two items more clearly defines the global intent, which is to measure the vulnerability of the structure to a seismic event.

Participants 3, 23, 24 and 26 refer to vulnerability and resistance to “ship” and “vessel” collisions. The researcher expected collisions in general (i.e. ships, vessels, and trucks) be accounted for using the Underclearances item, because with inadequate Underclearances the potential for a vehicular or vessel impact increases. However, parallel to the seismic items there are two aspects of collision vulnerability. The researcher intended the Underclearances item to account for the, the probability of the event occurring. However, the Underclearances item does not necessarily account for the probability of failure during that event. Typically, considerations in the initial design of the bridge or a retrofit, account for the potential of collapse after a collision. For example, a design engineer may protect bridge bents or piers with barrier rails or crash walls, thus minimizing the potential for collapse. Therefore, like with the seismic items renaming the Underclearances item to “Collision Exposure” well-defines the overall intent of the item within the Hazard Resistance Component.

In addition, it appeared that participants 4, 21, 23 and 30 misunderstood the Structure Type item. The researcher attempted to account for fracture critical bridges and those with fracture critical members, along with bridge types that require a more complex engineering analysis and design (i.e. suspension and cable-stayed bridges), with the Structure Type item. While highly complex bridges might be more vulnerable to external hazards, they are uncommon as there are only 97 suspension bridges and 43 cable-stayed bridges according to the latest NBI data (FHWA, 2010). However, the fact that a bridge is fracture critical remains important as demonstrated by the four comments and because the collapse of the Silver Bridge in 1967 and the I-35W Bridge in 2007 were due to the failure of fracture critical members. Therefore, it is deemed that the Structure Type item be renamed to "Fracture Critical Status" to simply delineate fracture critical bridges and leave other aspects to be considered through customization by the specific users.

Finally there were additional comments from participants that recommended combining the Scour Critical, Channel and Channel Protection and Waterway Adequacy items into a single item such and Hydraulic Vulnerability under the Hazard Resistance Component. While all of these items deal with a high hydraulic flows and flood events, they capture a different aspect of the event as defined in the *Recording and Coding Guide*.

The Channel and Channel Protection,

> "item describes the physical conditions associated with the flow of water through the bridge such as stream stability and the condition of the channel, riprap, slope protection, or stream control devices including spur dikes. The inspector should be particularly concerned with visible signs of excessive water velocity, which may affect undermining of slope protection, erosion of banks, and realignment of the stream, which may result in immediate or potential problems. Accumulation of drift and debris on the superstructure and substructure should be noted on the inspection form but not included in the condition rating" (FHWA, 1995, p. 40).

Whereas the Waterway Adequacy item (FHWA, 1995, p. 56) addresses the potential for a channel to overtop the bridge.

> "[It] appraises the waterway opening with respect to passage of flow through the bridge. The following codes shall be used in evaluating waterway adequacy (interpolate where appropriate). Site conditions may warrant somewhat higher or lower ratings than indicated by the table (e.g., flooding of an urban area due to a restricted bridge opening). Where overtopping frequency information is available, the descriptions given in the table for chance of overtopping mean the following:
>
> - Remote - greater than 100 years
> - Slight - 11 to 100 years
> - Occasional - 3 to 10 years

- Frequent - less than 3 years

Adjectives describing traffic delays mean the following:

- Insignificant - Minor inconvenience. Highway passable in a matter of hours.
- Significant - Traffic delays of up to several days.
- Severe - Long term delays to traffic with resulting hardship"

The definition of Scour Critical is

> "the current status of the bridge regarding its vulnerability to scour. Scour analyses shall be made by hydraulic/geotechnical/structural engineers. … A scour critical bridge is one with abutment or pier foundations which are rated as unstable due to (1) observed scour at the bridge site or (2) a scour potential as determined from a scour evaluation study" (FHWA, 1995, p. 75).

Given the previous definitions, the researcher considers the items distinct enough to be isolated within the Hazard Resistance Component.

Incorporating the changes discussed in this and previous sections will not only address what seemed to be misunderstanding and confusion by participants, but will better represent the objectives of this research, to determine the items and their relative weights in a general sense.

5.2.3 Discussion on Possible Participant Confusion in Completing the Survey

Upon receipt of responses and corresponding comments it appeared that there might have been misinterpretation among the participants with regards the categorizing of specific items within a particular component as well as the overall intent and purpose of those items. In turn, this may have led to confusion on how to complete the survey, and promoted the development of "debatable items". This section provides commentary about possible confusion and "debatable items" associated with participant comments listed in Table 32, Table 34 and Table 35.

Table 35: Participant Comments Demonstrating Possible Confusion

Participant Number	Participant Comments
Participant 1	• *Bridge Railing:* [Move to] Impact on Public. Not a structural component but safety feature used to protect the public • *Posting:* [Move from Structural Condition to] Impact on public

Participant 2	• *Impact on Public:* [Add Item] Add capacity.
Participant 5	• *Impact on Public:* [Add Item] Bridge roadway width.
Participant 7	• *Impact on Public:* [Add Item] Is this structure contributing to this being a high accident location on the system
Participant 8	• *Structural Condition:* [Comment] The superstructure should also have protective systems similar to the deck.
Participant 15	• *Impact on Public:* [Comment] Bridge Railing also shows up in the Structural Condition Components
Participant 18	• *Deck Geometry:* [Comment] I would be more concerned with the roadway approach onto the bridge. Is there adequate approach guardrail and approach treatments.
Participant 21	• *Protective Systems:* [Comment] Should include steel coating
Participant 28	• *Structural Condition:* [Add Item] Include wearing surface with protective system.

In light of the comments offered by participants 1 and 2, it is important to note, as discussed in Sections 3.2.1.1 and 3.2.1.2, that the listing of the Posting item under both the Structural Condition and the Impact on Public Components for two separate and distinct reasons. Posting was included under the Structural Condition Component because there is potential for a reduction in the structural capacity due to deficiencies, whether they are from deterioration over time or an event that caused serious damage (i.e. earthquake, flood, and vehicular impact). It was included under the Impact on Public Component to assess its influence on the traveling public through induced restrictions on heavy vehicles.

Additionally, Table 16 shows that Posting was a "debatable item", and Table 17 shows that all ten of the participants who selected "disagree and move" for the Posting item, chose the Impact on Public Component. It is hypothesized by the researcher that this is an indication that many of the participants who selected the Posting item to be moved, did not realize that the item already appeared in the Impact on Public Component, or did not understand the reasoning for categorizing it in the Structural Condition Component. Confusion may have increased, or be the primary cause of Posting being classified as a “debatable item”.

Although Posting was the primary item that exhibited potential confusion, there were additional comments indicating misunderstanding amongst participants. A possible reason for this is that some participants may not have carefully reviewed the background document (Appendix C) prior to filling out the survey portion (Appendix D) as annotated in the following paragraphs.

The results illustrated in Table 16 categorize two of these items, Bridge Railing and Approach Slabs, as “debatable items”. The researcher speculates that possible confusion further augmented the Bridge Railing dispute as demonstrated by the comments made by participants 1 and 15; where it appears the participants missed the distinctly different reasons for including Bridge Railing in both Structural Condition and Impact on Public Components as stated in Sections 3.2.1.1 and 3.2.1.2.

Participant 5 suggested the addition of a Bridge Roadway Width, and Participant 7 suggested adding and item to account for a “structure contributing to … a high accident location”; however, the researcher anticipated that the justification given for Deck Geometry Item accounts for both the bridge roadway width, and how the bridge conforms to current design and safety standards. Next, researcher envisioned that the Approach Roadway Alignment, as defined in Section 3.2.1.2, would partially account for the suggestion offered by participant 18. However, the approach guardrail, while integrated with Item 36 - Bridge Railing in the FHWA Recording and Coding Guide, was not intended to be part of the Bridge Railing item for this research, but could be included by customizing the resulting bridge management components. Finally, it was intended by the researcher that the Protective Systems item would account for all protective systems as defined by the new *AASHTO Guide Manual for Bridge Element Inspection*: “systems [that] will influence the deterioration and condition of the underlying structural element…wearing surfaces and protective coatings” (AASHTO, 2011, pp. 3-125). As such, it would include those items noted by participants 8, 21, and 28. However, the background document sent to the participants stated that “Protective Systems such as wearing surfaces or protective coatings are used to extend the useful life of the Deck/Slab”, which makes it, appear that the Protective Systems are limited to the Deck/Slab. Therefore, the intention of the researcher was not clear and the researcher should have included the aforementioned language from the *AASHTO Guide Manual*.

In general, there appeared to be a fair amount of confusion with this survey and the researcher realizes there were areas with room for improvement. A change in the format may have clarified several of these issues. Rather than having the definitions and justification for the proposed items in a background document, placing them right next to the respective item in the survey document, see Figure 23, would have increased the probability that all participants would carefully read the definition and justification prior to making their suggestion.

- **Posting (Structural Condition)**: If a bridge is posted or closed due to deficiencies, whether they are from deterioration over time or an event that caused serious damage (e.g. earthquake, flood, vehicular impact) this status should influence the Structural Condition Component.

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **Posting (Impact on Public)**: If a bridge is posted or closed due to deficiencies it may impact the traveling public by inducing route restrictions on heavy vehicles

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

Figure 23: Possible Format Change to Items Questionnaire

5.2.4 FINAL RECOMMENDED BRIDGE MANAGEMENT COMPONENT STRUCTURE INCLUDING ITEMS AND WEIGHTING FACTORS

The revisions of the results presented in Chapter 4 and Table 31 occur because of the survey results, comments, suggestions, and modifications discussed in previous sections. The final items that make up each component, the components themselves, and their relative importance are shown in Tables 36 and 37 and further explained below the table.

Table 36: Finalized Items Along with Their Relative Importance

Structural Condition Component		Preservation and Maintenance Component		Impact on Public Component		Hazard Resistance Component	
Items	**Relative Importance**	**Items**	**Relative Importance**	**Items**	**Relative Importance**	**Items**	**Relative Importance**
Superstructure / Slab	0.26	Deck	0.39	Posting	0.30	Scour Critical	0.31
Posting	0.23	Joints	0.23	Approach Roadway Alignment	0.12	Seismic Adequacy	0.17
Substructure	0.21	Protective Systems	0.15	ADT and ADTT	0.12	Collision Exposure	0.16
Deck	0.12	Bridge Railing	0.15	Under-clearances	0.11	Channel and Channel Protection	0.14
Inventory Rating	0.10	Approach Slabs	0.08	Deck Geometry	0.10	Waterway Adequacy	0.12
Bearings	0.08			Detour Length	0.09	Fracture Critical Status	0.10
				Bridge Railing	0.09		
				STRAHNET Designation	0.07		
Customized Item(s)	0.00	Customized Item(s)	0.00	Customized Item(s)	0.00	Customized Item(s)	0.00

Table 37: Finalized Bridge Management Components Along with Their Relative Importance

Components	Relative Importance
Structural Condition	0.43
Preservation and Maintenance	0.13
Impact on Public	0.25
Hazard Resistance	0.19

It is evident from the wide range of suggested items as shown in Tables 22 through 24 and the number of comments listed in Appendix G that there is need for customization. Therefore, an item titled "Customized Item(s)" is included at the end of each bridge management component.

This will enable and encourage potential users to customize the bridge management components to their particular needs, better complementing their current bridge management practices and enhancing tradeoff analyses. Additionally, the development of the Preservation and Maintenance Component and transfer of some items from the existing components to that component required adjustment of the relative importance values of the remaining items, while keeping their proportional ratios intact, to maintain a summation of 100. A summary of the revisions between Table 31 and Table 36, and between Table 29 and Table 37 are as follows:

- Structural Condition Component
  - Superstructure (0.22 → Superstructure / Slab (0.26
  - Posting (0.19) → Posting (0.23)
  - Substructure (0.18) → Substructure (0.21)
  - Modified Deck / Slab (0.10) → Deck (0.12)
  - Inventory Rating (0.08) → Inventory Rating (0.10)
  - Bearings (0.07) → Bearings (0.08)
  - Removed Joints
  - Removed Protective Systems
  - Removed Bridge Railing
  - Removed Approach Slabs
- Preservation and Maintenance Component
  - Added Joints
  - Added Protective Systems
  - Added Bridge Railing
  - Added Approach Slabs
  - Added Deck / Slab
  - Modified Deck / Slab (0.10) → Deck (0.39)
  - Joints (0.06) → Joints (0.23)
  - Protective Systems (0.04) → Protective Systems (0.15)
  - Bridge Railing (0.04) → Bridge Railing (0.15)
  - Approach Slabs (0.02) → Approach Slabs (0.08)
- Hazard Resistance Component
  - Seismic Design (0.10) + Seismic Zone (0.07) → Seismic Adequacy (0.17)
  - Modified Underclearances (0.16) → Collision Exposure (0.16)

    - Modified Structure Type (0.10) → Fracture Critical Status (0.10)
- Relative Weighting Factors of Components
    - Modified Structural Condition (0.56) → Structural Condition (0.43) & Preservation and Maintenance (0.13)

5.3 Potential Utilization and Implementation Strategies of Research Results

The specific application of the bridge management components by bridge managers and decision makers is beyond the scope of this research. However, this section offers discussion about potential uses.

5.3.1 Graphical Representation of Bridge Management Components

Graphing the isolated bridge management components offers decision makers a quick visual of several bridges within their network and enables them to perform tradeoff analyses. This graphical representation would be similar to the Sufficiency Rating or a BHI in that it utilizes bridge items (i.e. NBIS items and AASHTO CoRe elements), but would illustrate and highlight characteristic variations among bridges by means of distinct bridge management components rather than combining everything into a single rating or index.

For example, a bridge manager may be interested in developing an inspection cycle and inspection frequencies for a select set of bridges. In doing so they determine they are going to base their decision on the structural adequacy and the vulnerability to hazards for each bridge. As a result, the bridge manager assigns the Structural Condition and Hazard Resistance Components to an axis, forming a two-dimensional graph. The manager selected these criteria because they feel a bridge with a high level of structural adequacy and a low vulnerable to hazards could be inspected less frequently. Finally, the component ratings for each bridge are plotted as illustrated by Figure 24.

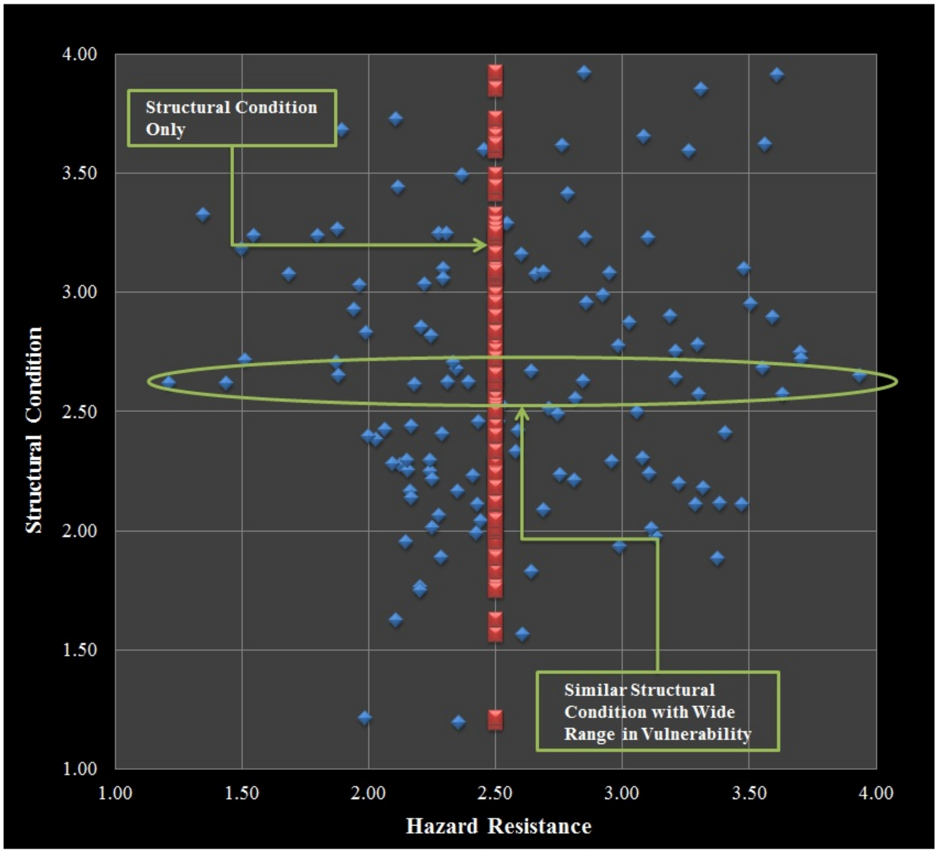

Figure 24: Example of Bridges Plotted on a Two-Dimensional Graph.

As shown, the two-dimensional graph differentiates and distributes bridges with effectively the same rating for the Structural Condition Component, and subsequently the user can easily visualize and interpret the results. In addition, the graph shows that even though a bridge is in "good" structural condition, it may be "highly" vulnerable to hazards and thus would not be a good candidate for an extended inspection cycle, and may even require a shortened inspection cycle. As previously mentioned in Section 1.3, WYDOT is considering using this application.

The details of rating and scoring each item are beyond the scope of this research, but for illustrative purposes, the researcher assumes that inspection data defines the ratings of each item and the rating scale is the same as defined in the new *AASHTO Guide Manual* (AASHTO, 2011). This scale ranges from one to four, with one being the best and four being the worst. Each item's inspection rating is then multiplied by its relative weighting factor, as determined by this research, to obtain the relative rating. After that the items' relative ratings are summed for the overall rating for a given bridge management component. Table 38 provides an example of these calculations.

Table 38: Sample Calculation for Structural Condition Rating

Structural Condition Item	Item Rating	Relative Weight	Relative Item Rating
Superstructure / Slab	3	0.26	0.78
Posting	2	0.23	0.46
Substructure	2	0.21	0.42
Deck	1	0.12	0.12
Inventory Rating	2	0.10	0.2
Bearings	1	0.08	0.08
Structural Condition Rating		2.06	

Furthermore, reviewing a selected set of bridges on a two-dimensional graph may help prioritize structures when making funding decisions through tradeoff analyses. For example, there may be bridges with a high Preservation and Maintenance Rating, which when using a "worst-first" approach to bridge management, would typically prioritize these structures for maintenance, rehabilitation and repair work. However, some of these bridges may have a low Impact on Public rating, indicating that the "poor condition" of the bridge has very little influence on the traveling public. Conversely, bridges with a low Preservation and Maintenance rating, and a high Impact on Public rating indicates that even though the bridge may not be in the "worst condition" it may warrant maintenance first due to the high level of influence on the traveling public. Some current BMSs such as Pontis incorporate deterioration models, conduct optimization scenarios, and run cost benefit analyses, and while all of these are valuable, the previous analysis would be difficult for bridge management engineers to conduct when using a single rating or index (i.e. Sufficiency Rating or BHI), but easily seen given the quick visual shown in Figure 25.

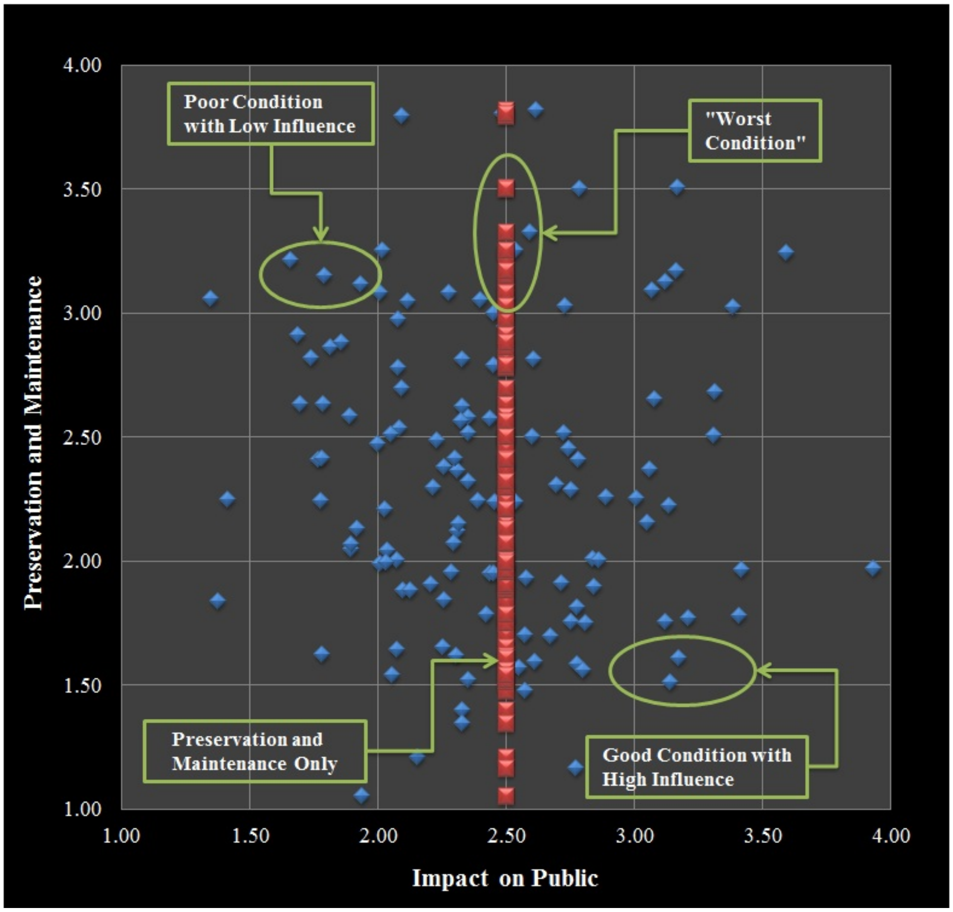

Figure 25: Example of Bridges Plotted on a Two-Dimensional Graph.

In addition to the practical applications provided through two-dimensional graphs, there may be benefits to bridge management engineers by utilizing a three-dimensional graph to assess the overall state of a set of bridges selected for project planning as shown in Figure 26.

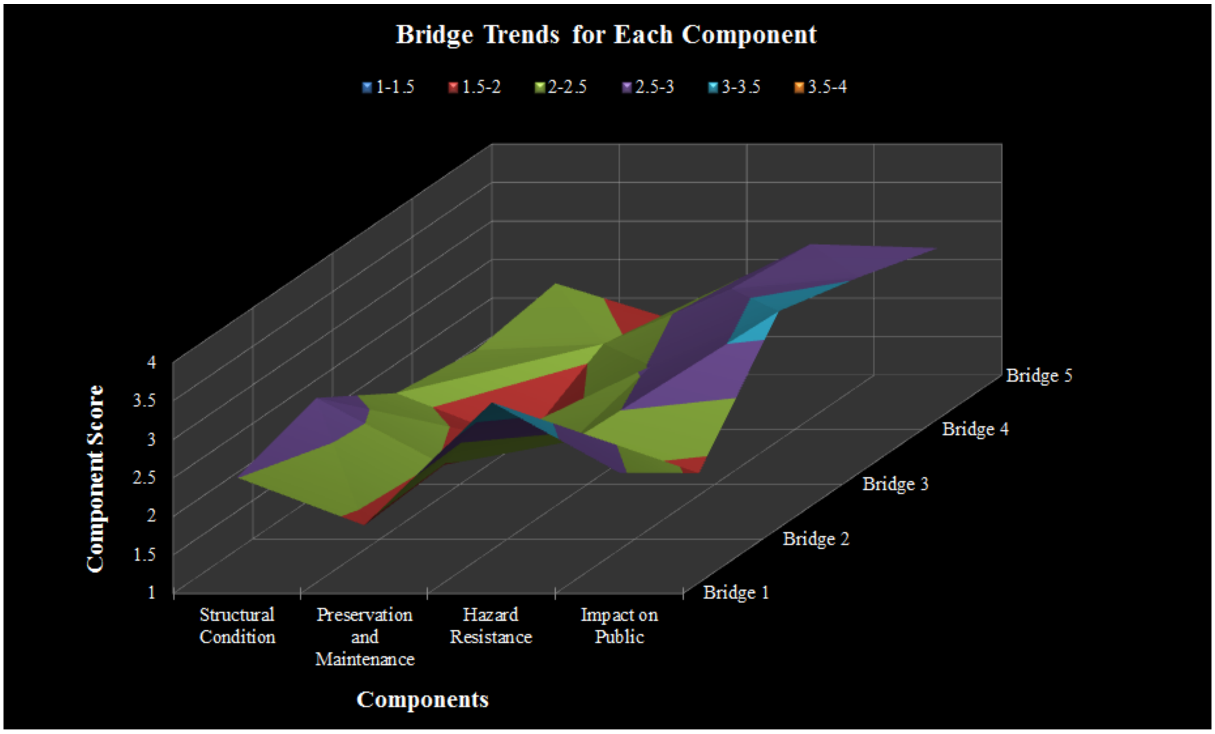

Figure 26: Example of a Selected Set of Bridges Plotted on a Three-Dimensional Graph

5.3.2 UTILIZATION OF MULTI-CRITERIA DECISION ANALYSIS SUCH AS AHP

In addition, to making use of the graphical representation of the bridge management components for practical applications as discussed in the preceding section, decision makers and bridge management engineers could integrate and apply the bridge management components as criteria in the AHP. As discussed in Section 3.3.1 AHP is a multi-criteria decision analysis method that assists decision makers in logically reasoning through the advantages and disadvantages of decision alternatives "[while providing] … the objective mathematics to process the inescapably subjective and personal preferences of an individual or group in making decisions" (Saaty & Vargas, 2001, p. 12 & 27). While the AHP is valuable in making multi-criteria decisions, this research only used the mathematical matrices to determine the relative importance of items.

Upcoming discussion in Section 5.4 observes the significant research attention devoted to bridge management. This attentiveness is in part due to the complexity of bridge management given that it is comprised of many related factors, and thus traditional logical thinking "leads to sequences of ideas that are so tangled that their interconnections [they] are not readily discerned" (Saaty T. L., 1994, p. 20). Therefore, bridge managers, decision makers and researchers alike have identified the need to investigate and develop effective multi-criteria decision-making tools.

The researcher recommends employing the AHP with bridge management components because the hierarchies are simple to construct, it is adaptable to both groups and individuals, and it embraces intuitive thought, encourages compromise and consensus building, and is a basic approach to decision-making that reveals all interrelationships and tradeoffs (Saaty T. L., 1994).

Figure 15 in Section 3.3.1.1, showed the procedure for creating a decision structure (hierarchy) that consists of the decision goal at the top, the potential alternatives at the bottom and the criteria and sub-criteria for evaluating the alternatives in the middle. When integrating bridge management components (using only a single component, as seen in Figure 27, or multiple components, illustrated in Figure 28) the four components defined in Section 5.2.4 are the primary criteria and their related items and respective weighting factors are the sub-criteria.

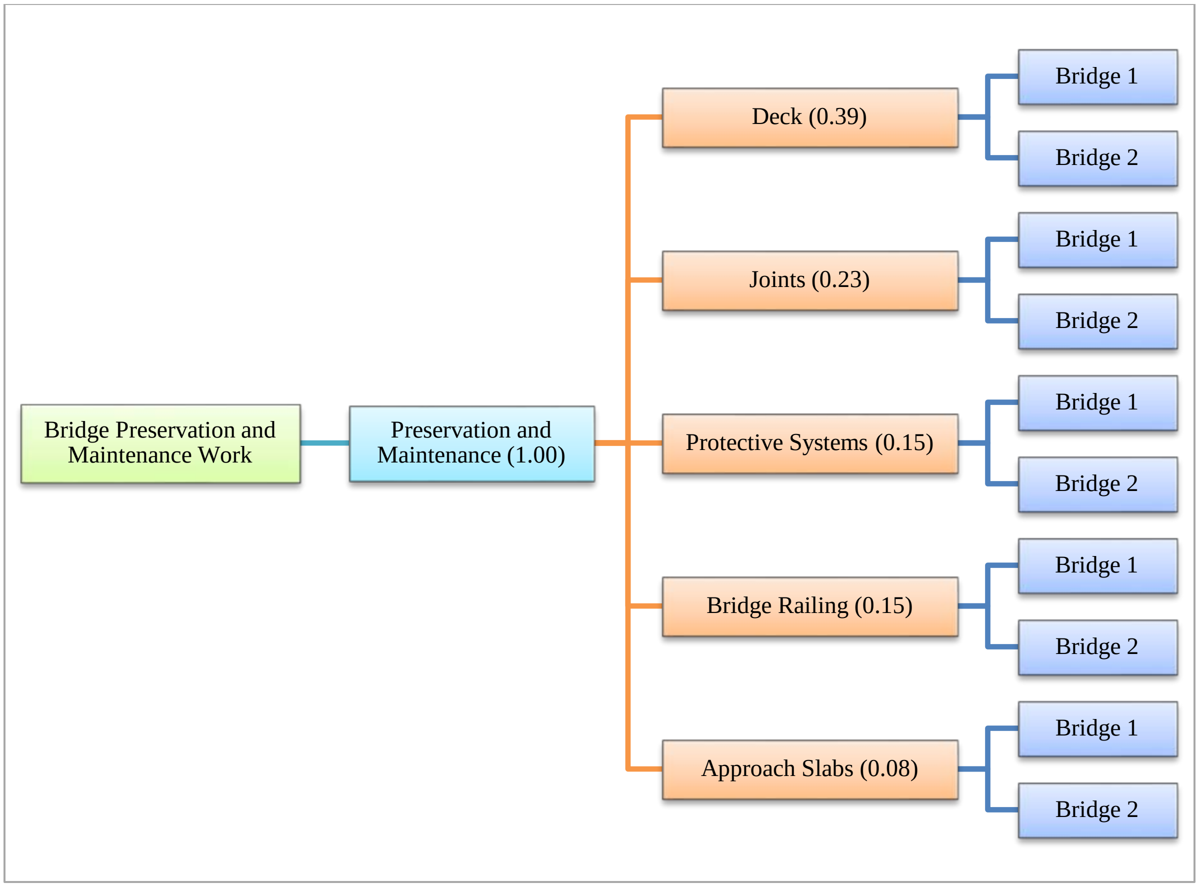

Figure 27: Hierarchy for Bridge Preservation and Maintenance Prioritization

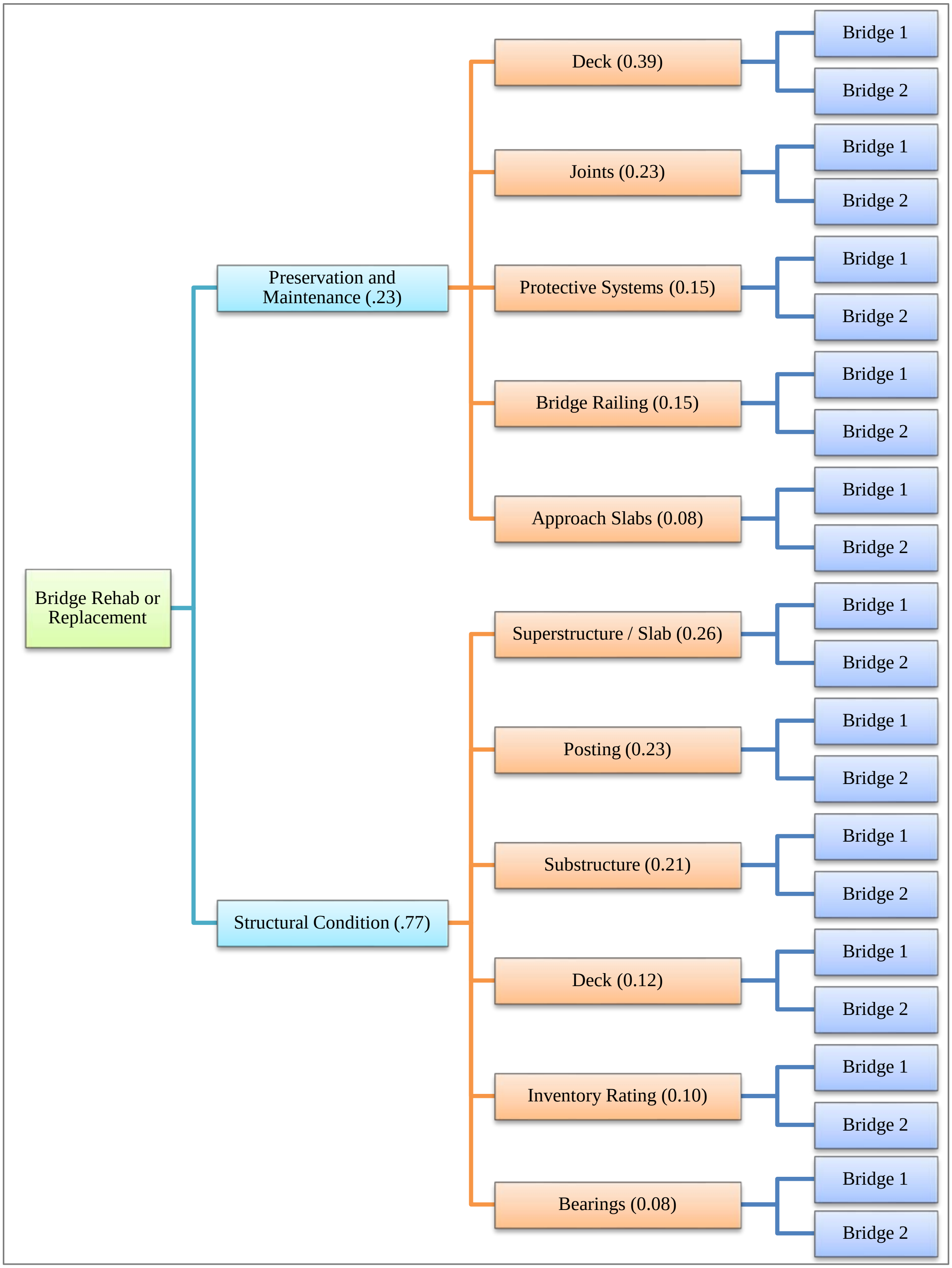

Figure 28: Hierarchy for Bridge Rehabilitation and Replacement Prioritization

Note that in Figure 28 that the weighting factors for the items did not change from their values listed in Table 36, however the component weighting factors did change. This occurs because the AHP requires that the summation of the weight factors at every level equal one. Therefore, a component's relative weighting factor is dependent upon the bridge management components applied and it is proportional to its relative ratio to the other factors as determined by this research. Provided are hypothetical example calculations for Figure 28 to highlight the full utilization of the AHP. As previously stated, the details of rating each item are beyond the scope of this research, but process for calculating the ratings for each bridge management component is the same as shown in Table 38. To arrive at the overall rating for each bridge, the component rating is multiplied by its related weighting factor and then added to the ratings for the other components under consideration as shown by the following calculations.

Decision Goal – Determine Which Bridge to Rehabilitate or Replace

$\underline{\textit{Preservation and Maintenance Rating (Bridge 1):}}$

$$\textit{Deck (Non-Structural)} = 1 \Rightarrow 1 \times 0.39 = 0.39$$

$$\textit{Joints} = 1 \Rightarrow 1 \times 0.23 = 0.23$$

$$\textit{Protective Systems} = 4 \Rightarrow 4 \times 0.15 = 0.60$$

$$\textit{Bridge Railing} = 4 \Rightarrow 4 \times 0.15 = 0.60$$

$$\textit{Approach Slabs} = 2 \Rightarrow 2 \times 0.08 = 0.16$$

$$\textit{Perservation and Maintenance Rating (Bridge 1)} = 0.39 + 0.23 + 0.60 + 0.60 + 0.16 = \underline{1.98}$$

$\underline{Structural\ Condition\ Rating\ (Bridge\ 1):}$

$Superstructure\ /\ Slab = 1 \Rightarrow 1 \times 0.26 = 0.26$

$Posting = 2 \Rightarrow 2 \times 0.23 = 0.46$

$Substructure = 3 \Rightarrow 3 \times 0.21 = 0.63$

$Deck\ (Structural) = 1 \Rightarrow 1 \times 0.12 = 0.12$

$Inventory\ Rating = 4 \Rightarrow 4 \times 0.10 = 0.40$

$Bearings = 3 \Rightarrow 3 \times 0.08 = 0.24$

$Structural\ Condition\ Rating\ (Bridge\ 1) = 0.26 + 0.46 + 0.63 + 0.12 + 0.40 + 0.24 = \underline{2.11}$

$\boldsymbol{Overall\ Rating\ (Bridge\ 1) = (0.23 \times 1.98) + (0.77 \times 2.11) = \underline{\underline{2.08}}}$

$\underline{Preservation\ and\ Maintenance\ Rating\ (Bridge\ 2):}$

$Deck\ (Non\text{-}Structural) = 2 \Rightarrow 2 \times 0.39 = 0.78$

$Joints = 3 \Rightarrow 3 \times 0.23 = 0.69$

$Protective\ Systems = 1 \Rightarrow 1 \times 0.15 = 0.15$

$Bridge\ Railing = 3 \Rightarrow 3 \times 0.15 = 0.45$

$Approach\ Slabs = 2 \Rightarrow 2 \times 0.08 = 0.16$

$Perservation\ and\ Maintenance\ Rating\ (Bridge\ 2) = 0.78 + 0.69 + 0.15 + 0.45 + 0.16 = \underline{2.23}$

$\underline{Structural\ Condition\ Rating\ (Bridge\ 2):}$

$Superstructure\ /\ Slab = 3 \Rightarrow 3 \times 0.26 = 0.78$

$Posting = 1 \Rightarrow 1 \times 0.23 = 0.23$

$Substructure = 3 \Rightarrow 3 \times 0.21 = 0.63$

$Deck\ (Structural) = 2 \Rightarrow 2 \times 0.12 = 0.24$

$Inventory\ Rating = 1 \Rightarrow 1 \times 0.10 = 0.10$

$Bearings = 4 \Rightarrow 4 \times 0.08 = 0.32$

$Structural\ Condition\ Rating\ (Bridge\ 2) = 0.78 + 0.23 + 0.63 + 0.24 + 0.10 + 0.32 = \underline{2.30}$

$\boldsymbol{Overall\ Rating\ (Bridge\ 2) = (0.23 \times 2.23) + (0.77 \times 2.30) = \underline{\underline{2.28}}}$

While the AHP calculates an overall single value rating similar to the Sufficiency Rating and BHI, it is more effective for decision-making and conducting tradeoff analyses because of its inherent attribute of customizability. Additionally, the BHI accounts for bridge elements that can deteriorate (e.g. Deck, Girders, etc.), but neglects other features and characteristics related to bridges.

This research provides decision makers and bridge management engineers with effective, well-defined, and customizable bridge management components, as well as their related items and corresponding weighting factors as shown in Tables 36 and 37. These components account for a wide range of bridge attributes, and can effectively illustrate the performance of the bridges within a transportation network.

5.4 Contribution to the Body of Knowledge and Commentary About the Purpose and Merits of this Research

As discussed and demonstrated in the previous sections, the primary contribution of this research is to provide bridge management engineers and decision makers with effective bridge management components that clearly distinguish differences in bridge attributes that may go unnoticed when using a single rating or index through a two part survey that included a questionnaire and methodological approach (AHP). Transportation agencies may utilize the established components, based on input from 58% of State DOTs, in a variety of ways to develop customized BMSs and conduct tradeoff analyses that complement their current bridge management practices, which in turn may better illustrate the operation of bridges in their system.

Both participants and non-participants (those who responded to the solicitation email but did not fill out any part of the survey) made unanticipated, but valuable critiques regarding this research. The following is a presentation of these comments along remarks and commentary from the researcher.

Comment 1 – Participant 9:

> "Honestly, I fail to see the usefulness of this questionnaire or the research project in general. The NBI already identifies practically all of the non-structural items. Pontis, probably the most commonly used BMS software, identifies the structural components via the Core Elements. I'm just unclear what this adds that isn't already available."

Researcher Remarks on Comment 1:

The researcher agrees with the assertion that between the *AASHTO Guide for Commonly Recognized (CoRe) Elements* and the FHWA *Recording and Coding Guide* most of the proposed items listed in Chapter 3 are included. However, neither of the publications accout for either the seismic zone or seismic design items, so they are considered to be additional items. Furthermore it was not the intent of this research to simply try to identify a series of "new / additional" bridge managment items. Rather this research was an attempt to address and improve upon the drawbacks and shortcomings inherent with the current structure and organiziation of bridge management items by isolating these items and then categorizing them under distinct bridge management components that have a defined objective.

Comment 2 – Non- Participant:

> "This is a difficult questionnaire for me to answer because it appears to cover issues that have already received a lot of attention over the past few years, and for which there are quite a few reports documenting a consensus among bridge managers about performance measurement. You might want to take a look at the following publications: AASHTO Bridge Element Inspection, Manual Multi-Objective Optimization for Bridge Management Systems, AASHTO Transportation Asset Management Guide: Focus on Implementation. These describe the condition and performance measures most widely used for bridge management today. The items mentioned in the questionnaire are a part of it, but there is much more."

Researcher Remarks on Comment 2:

Again, the researcher agrees that there has been significant attention given to issues relating to bridge management, as is evident by the large amount of literature reviewed and cited in Section 2.4 and Appendix A of this document; note Section 2.4.3 reviews the NCHRP 590 report noted in this comment. However, most sources focus primarily on deterioration and how it relates to maintenance, rehabilitation and replacement, whereas this research focuses on identifying multiple criteria along with their relative importance to supplement current BMSs and provide further decision analysis methods for decision-makers in transportation agencies.

Comment 3 – Non- Participant:

> "Every one of the items on the questionnaire is included for example in the New York State bridge inventory (and to some extent in NBI). New York State also has 7 vulnerability manuals. New York City has a maintenance package supplementing the NYS database. It can optimize the application of 15 maintenance tasks, based on certain assumption under constraints. A general description of all these features can be found in Bridge Management by Yanev, Wiley, 2007."

Researcher Remarks on Comment 3:

The researcher realizes that there are many bridge management items already established, but this research deals with how those items are categorized and utilized. Moreover, the researcher appreciated and welcomed other similar comments that provide information about current practices and references to additional research.

Comment 4 – Participant 34:

> "You should really make sure to get a copy of the new AASHTO Bridge Element Inspection Manual - it has addressed several of these areas explicitly."

Researcher Remarks on Comment 4:

Again, the researcher reviewed and used the literature cited in this comment to help determine the lists of proposed items. Note that mentioned document simply identifies the items, but does not focus on their relative importance between the items.

Comment 5 – Non- Participant:

> "I'm confused. I've read the attachments, and it seems like you are rehashing the Sufficiency Rating (S/R). The S/R is made up of the following three components: Structural Adequacy and Safety, Serviceability and Functional

> Obsolescence, and Essentiality for public use. (Figure 1 Summary of Sufficiency Rating Factors. Page B-2) You may be able to improve on that in the eyes of some State Transportation Departments (STDs), but the bottom line is that I don't' see how this process will benefit Bridge Management. There was no mention of bridge maintenance anywhere in the transmittal or the attachments; or it was so insignificant that I missed it. FHWA went down the Bridge Management road back in the 1980s due to the need to get away from the combination of worst first project selection and no consideration of maintenance. What I see here is perhaps a revision of the S/R but I don't see where maintenance optimization even enters into the process. There was a lot left unspoken. I can see where your method would be better than reliance on the S/R as it exists, but I'd hesitate to call it Bridge Management."

Researcher Remarks on Comment 5:

Unlike the previous four comments, it appears this professional understood that the primary goal of this research was to "improve" upon the drawbacks and shortcomings inherent with utilizing the Sufficiency Rating for bridge management purposes. However it is argued that this will intrinsically benefit decision-makers and bridge management engineers. The comment regarding maintenance is similar to other comments that specified a need to develop a fourth bridge management component to address maintenance was discussed in Section 5.2.1.

5.5 FUTURE RESEARCH

During the course of this study, the researcher recognized scoping limitations with this research and identified areas that expand upon this study, as possible future research.

1. **Develop a study to verify the conclusions and modifications to the components and items as listed in Tables 36 and 37:** The study would likely be two part survey similar to this research, but utilizing a modified format as presented in Figure 23 for the items survey. Although reminiscent of this study, it may be necessary due to the changes applied to the original components and proposed items. Furthermore, this follow-up research possibly could involve interviews or focus groups.
2. **Investigate and incorporate other notable comments received from participants of this research not used to modify the components or their respective items:** For

example, there were comments (as discussed in Section 5.2.1) related to isolating bridge elements that make up the superstructure and substructure into separate items, and comments (as discussed in Section 5.2.2) related to merging the Scour Critical, Channel and Channel Protection and Waterway Adequacy items. While the researcher provided commentary on these recommendations, there may be a need for further discourse, through interviews or focus groups, to investigate these potential changes. Additionally there were comments related to how public perception and politics influence the maintenance, rehabilitation and repair of bridges. A research study could be developed in an attempt to quantify this observable fact. Finally, there were comments from several participants that mentioned the notion of "safety". While it was assumed by this research that safety is an inherent overall goal of bridge management, specifically addressing "safety" as an objective for tradeoff analysis may be a needed.

3. **Determine a method for evaluating and scoring the components and items:** As discussed in Section 5.3, this was beyond the scope of this research study. Therefore potential future research could provide a method for developing a common scale for the components and items, possibly through value and utility functions.

4. **Develop an optimization process and framework for an efficient bridge inspection program:** While this research and most of the literature reviewed by this research focus on bridge preservation and maintenance, there is an established need to utilize BMSs to help determine inspection frequency and create inspection cycles in addition to preservation and maintenance decisions. Furthermore, decision makers acknowledge that a bridge management program is only as good as the inspection data it relies upon. The optimization model should enable end user customizability.

5. **Expound upon this research by creating a framework for a computerized application, utilized by bridge managers in State DOTs for developing a systematic bridge preservation and maintenance plan, which incorporates the findings of this**

study as well as other future research mentioned in this section: The application framework should emphasize end user customizability and incorporate a decision analysis process similar to the AHP. This research would require the development of an optimization process, which would include construction of deterioration models and life cycle cost models. In addition, the research should consider including long-term sustainability analysis for the materials and construction methods used. The need for bridges to last long-term is evident through the vast amount of literature on bridge management referenced by this research and the current research project (*SHRP 2 R19 (A) for Service Life beyond 100 Years: Innovative Systems, Subsystems, and Components*) which is evaluating an extension in the design life of a bridge from 75 years to 100 years.

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APPENDIX A – LITERATURE AND PUBLICATIONS CONCERNING BRIDGE MANAGEMENT

I. Methods for Capital Programming and Project Selection – NCHRP Synthesis 243 (Neumann, 1997)

II. Current Status of Bridge Management System Implementation in the United States (Small, Philbin, Fraher, & Romack, 1999)

III. A Geographic Information Systems (GIS) Based Bridge Management System (She, Aouad, & Sarshar, 1999)

IV. BRIGEIT: User-Friendly Approach to Bridge Management (Hawk, 1999)

V. AASHTO Commonly-Recognized Bridge Elements – Successful Applications and Lessons Learned (Thompson & Shepard, 2000)

VI. Bridge Management System and Maintenance Optimization for Existing Bridges (Miyamoto, Kawamura, & Nakamura, 2000)

VII. Evaluating Bridge Health - California's Diagnostic Tool (Shepard & Johnson, 2001)

VIII. Incorporation of Seismic Consideration in Bridge Management Systems (Mayet & Madanat, 2003)

IX. Pontis Bridge Management System - State of the Practice in Implementation and Development 9th Annual (Robert, Marshall, Shepard, & Aldayuz, 2003)

X. Risk-Based Expenditure Allocation for Infrastructure Improvement (Ayyub & Popescu, 2003)

XI. Analytical Tools for Asset Management – NCHRP Report 545 (Cambridge Systematics, Inc.; PB Consult; System Metrics Group, Inc., 2005)

XII. Monitoring Bridge Health Using Fuzzy Case-Based Reasoning (Cheng & Melhem, 2005)

XIII. Bridge Management - Experiences of California, Florida, and South Dakota (FHWA, 2005)

XIV. Probability-Based Bridge Network Performance Evaluation (Liu & Frangopol, 2005)

XV. System Risk Curves: Probabilistic Performance Scenarios for Highway Networks Subject to Earthquake Damage (Shiraki, et al., 2006)

XVI. Culvert Management Systems: Alabama, Maryland, Minnesota and Shelby County (FHWA, 2007)

XVII. Critical Review of New Directions in Bridge Management Systems (Darbani & Hammad, 2007)

XVIII. CoRe Concerns (Al-Wazeer, Harris, & Nutakor, CoRe Concerns, 2007)

XIX. Applying “Fuzzy Concept” to Bridge Management (Al-Wazeer, Harris, & Dekelbab, 2008)

XX. Optimizing Lifetime Condition and Reliability of Deteriorating Structures with Emphasis on Bridges (Frangopol, Neves, & Petcherdchoo, 2008)

XXI. Integrated Multiple-Element Bridge Management System (Elbehairy, Hegazy, & Soudki, 2009)

XXII. Using Soft Computing to Analyze Inspection Results for Bridge Evaluation and Management (Li & Burgueño, 2010)

XXIII. Proposal of an Integrated Index for Prioritization of Bridge Maintenance (Valenzuela, de Solminihac, & Echaveguren, 2010)

XXIV. The International Association for Bridge Management and Safety (IABMAS) Overview of Existing Bridge Management Systems (Adey, Klatter, & Kong, 2010)

XXV. Assuring Bridge Safety and Serviceability in Europe (Hida, et al., 2010)

XXVI. Comprehensive Risk Analysis for Structure Type Selection – CDOT Publication (Corotis, Beams, & Hattan, 2010)

XXVII. Framework for a National Database System for Maintenance Actions on Highway Bridges – NCHRP 668 (Hearn, Thompson, Mystkowski, & Hyman, 2010)

APPENDIX B – PARTICIPANT SOLICITATION E-MAIL

This e-mail is being sent to request your participation in a study conducted by Joshua Johnson under the supervision of Dr. Mehmet Ozbek in the Department of Construction Management at Colorado State University.

The purpose of this research is to investigate through a survey of professional and expert opinions, the concept of separating and categorizing bridge related items from a single rating or index (i.e. NBIS Sufficiency Ratio or Bridge Health Index)into more usable bridge management components (i.e. structural condition, impact on public and hazard resistance); by determining the appropriate items within each component as well as the respective relative weighting factor associated with each item.

You were specifically selected for participation in this study due to your expert qualifications, and I am hopeful that you will agree to assist in this study. It is important to note that there is no right or wrong answer; rather I am interested in obtaining your professional opinion in regards to bridge management. Your contribution is central in expanding the body of knowledge of this topic. You will be asked to review a list of proposed items for each component and then validate or make restructuring suggestions based on the components' objective/goal. It is estimated that the questionnaire will take approximately 30 minutes to complete. The final items for each component will be determined based on participant responses.

At a later date, when the final items have been identified, you will be sent a second form and asked to make paired comparison judgments to determine the appropriate weighting factor for each item. It is estimated that this form will take approximately 30 minutes to complete.

Please note that participation in this study is voluntary, there are no know direct risks or benefits to the participants and your name will not be used in publications resulting from this research. If you are willing to participate in this study, please review the attached document titled *Proposed Items* and then complete and return the questionnaire titled *Items Questionnaire.* If you have any questions or would like more information, please respond to this e-mail. Thank you for your time and I look forward to hearing from you.

Sincerely,
Joshua Johnson
Co-Principal Investigator

APPENDIX C – BACKGROUND INFORMATION AND INSTRUCTIONS FOR PROPOSED ITEMS QUESTIONNAIRE

BACKGROUND

The optimal allocation of resources to maintain a safe transportation system is a key objective of many transportation agencies. This is especially true under the current economic environment in which revenue streams have been either held the same or reduced. For decision makers, determining how to distribute funds between competing bridges is a challenging mission. A common tool used by managers in making these critical decisions is a Bridge Management System (BMS). BMSs are a designed to optimize the use of available resources for the inspection, maintenance, rehabilitation and replacement of bridges. Recently, *NCHRP Synthesis 397* investigated the current state of bridge management and how transportation agencies use BMSs to make decisions concerning bridges on their transportation network and some State DOTs and local agencies are pursuing and developing BMSs customized to their particular needs.

The purpose of this research is to investigate the concept of separating bridge related items from a single rating or index (i.e. Sufficiency Rating or Bridge Health Index) and then categorizing them into distinct bridge management components (i.e. structural condition, impact on public and hazard resistance) by determining the appropriate items within each component as well as the respective relative weighting factor associated with each item. Having isolated bridge management components provides decision makers the ability to clearly recognize variations among structures that could be overlooked when utilizing a single rating or index; and furthermore may help them develop a BMS for prioritizing work between bridges. It should be noted that the motivation for this research is adapted from the BMS being considered by the Wyoming Department of Transportation (WYDOT) (Fredrick, 2010).

Items that structure a bridge management component can be a major or minor element of a bridge (e.g. deck, girder, column, etc.), a characteristic of the bridge (e.g. vertical clearance, span length, roadway width, etc.) or an external feature that is associated with the bridge (e.g. seismic category, detour length, traffic volume, etc.) The related weighting factor is simply how much importance is placed on an item relative to the other items within the component.

MOTIVATION FOR RESEARCH

There is a general feeling in the field of bridge management that currently there is not a BMS that encompasses the needs of all transportation agencies. With this sentiment there are several bridge managers, agencies, and private companies attempting to develop a BMS that meets their specific needs and is effective at aiding in the decision making process. By breaking down a single rating into multiple components, decision makers in the industry may benefit by having another methodology for completing their asset/bridge management analysis. Once the bridge management components are identified, transportation agencies may utilize them in a variety of ways to develop BMSs.

PROPOSED ITEMS

Each bridge management component has a defined objective/goal and a list of proposed items that include a brief discussion. Please review the following lists and then complete the questionnaire where you will validate or make restructuring suggestions for each item under each component.

For example, you may check an agree box, which means you agree that the item belongs to and achieves that components objective/goal; check a disagree box, which means you feel that the item should be removed completely; or check a disagree box with an option to move the item to a different component (see items questionnaire).

The proposed items, as identified through a thorough literature review and the experience of the author, are as follows:

Structural Condition Component

The objective/goal of the structural condition component is to accurately measure the structural adequacy of a bridge. This may aid bridge managers in make bridge preservation and improvement decisions.

- **Deck/Slab** – The deck on a bridge or slab superstructure transfer loads to the supporting superstructure or substructure elements respectively. Examples include a timber deck, steel deck, reinforced concrete deck, and reinforced concrete superstructure. It should be noted that the Deck/Slab item does not include protective systems such as wearing surfaces.
- **Protective Systems** – Protective systems such as wearing surfaces or protective coatings are used to extend the useful life of the Deck/Slab.
- **Approach Slabs** – This item consists of any type of approach slab a bridge may have.
- **Bridge Railing**– Bridge railings include metal railings, concrete railings, timber railings, etc.
- **Joints**– Joints include all expansion devices such as strip seals, compression seals, open joints, etc.
- **Superstructure** – This includes all of the structural elements that make up the superstructure. Examples of superstructure elements include girders or beams, splice plates, lateral bracing (e.g. cross frames and diaphragms), stiffeners, stringers, floor beams, gusset plates, cables, and built up members such as truss members and arch members.

- **Bearings** – Bearings include all bearing devices such as fixed bearings, rocker bearings, elastomeric bearings, etc.
- **Substructure** – The substructure consists of all structural elements that represent the substructure such as abutments and bents/piers, which have several elements (i.e. cap, back wall, wingwalls, pedestals, columns, footings etc.). In addition, any effects from settlement would be included under this item.
- **Inventory Rating**– An inventory rating by definition is the load level which a bridge can safely support indefinitely (FHWA 1995). Inventory ratings are generally calculated for the superstructure, but can be calculated for substructures as well.
- **Posting** – If a bridge is posted or closed due to deficiencies, whether they are from deterioration over time or an event that caused serious damage, such as an earthquake, flood or vehicular impact, the posting should notably influence the structural condition.

Impact on Public Component

The objective/goal of the impact on public component is to evaluate how bridge attributes affect the traveling public and influence bridge management. Identifying these items may help decision makers prioritize bridgework.

- **Deck Geometry**– Assesses how the bridge conforms to current design and safety standards and considers the bridge roadway width and the vertical clearance over the bridge.
- **Underclearances**–Measures how the bridge conforms to current design and safety standards in regards to the horizontal and vertical clearances under the bridge.
- **Approach Roadway Alignment**– Evaluates how the alignment of the roadway approaches to the bridge relates to the general highway alignment for the section of highway the bridge is on.

- **Detour Length**– Detour length is included because alternative routes are an inconvenience for the user and it may add considerable travel time and cost.
- **Average Daily Traffic (ADT) and Average Daily Truck Traffic (ADTT)** – The volume of traffic is an indication about how essential a bridge is to the traveling public.
- **STRAHNET Designation**– Location and designation on the national highway system may suggest how important it is for abridge to remain open.
- **Bridge Railing** – Bridge railing under impact on public is an evaluation as to whether or not the bridge railing and its related parts are up to current design and safety standards rather than the actual condition of the railing as measured in the structural condition component.
- **Posting** – If a bridge is posted or closed due to deficiencies, it may influence the traveling public by inducing route restrictions on heavy vehicles.

Hazard Resistance Component

The objective/goal of the hazard resistance component is to evaluate how attributes and external factors affect the vulnerability of a bridge in regards to probability of an event as well as probability of failure. Potential events such as earthquakes, floods, or sudden impacts could be detrimental to a bridge. Therefore, determining a bridges level of hazard resistance may aid decision makers complete their bridge management analysis.

- **Scour Critical**–This item is to identify the status of a bridge regarding its vulnerability to scour based on a scour analysis. During a flood event there is a possibility for scour to occur and cause the loss of a bridge.
- **Channel and Channel Protection**–This item describes the physical conditions associated with the flow of water beneath the bridge such as stream stability and the condition of the channel. Inadequate channel protection or an unstable channel can

facilitate erosion can severely weaken the substructure and/or foundation and possibly cause the loss of a bridge.

- **Waterway Adequacy**–This item appraises the channel with respect to passage of flow through the bridge. Again, this item is important as it relates to potential flood events.
- **Seismic Zone** – The seismic zone or seismic design category (SDC) is related to the probability a bridge will undergo a seismic event along with the magnitude or intensity of that event.
- **Seismic Design** – This item is intended to capture a bridges ability to withstand a seismic event based on if it was designed or retrofitted for its appropriate seismic category. Seismic design is an important factor because of recent changes in how seismic zones are determined. These changes have placed many bridges in a higher seismic category. Thus, a bridge that was constructed several years ago may not incorporate certain seismic design considerations and will not perform as well during a seismic event.
- **Structure Type** – This is important because certain structure types require a more complex engineering analysis and design and may be more vulnerable to external hazards (i.e. fracture critical details, submerged elements, suspension bridges, arches etc.).
- **Underclearances** – This item is included under the hazard resistance because if the underclearances are inadequate the potential for a vehicular or vessel impact increases.

APPENDIX D – PROPOSED ITEMS QUESTIONNAIRE

RESPONDENT INFORMATION – (OPTIONAL)

Name:

Title:

Agency:

Address:

City: State: Zip:

Phone: Fax:

E-mail:

ITEMS QUESTIONNAIRE

Please check the appropriate box (Agree, Disagree - Remove, or Disagree – Move to for each given item. Please complete this portion of the survey by May17, 2011, and send it via email to jhnsn@rams.colostate.edu.

<u>Structural Condition Component</u>

- **Deck/Slab**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **Protective Systems**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to [ ]

- **Approach Slabs**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to [ ]

- **Bridge Railing**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to [ ]

- **Joints**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to [ ]

- **Superstructure**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to [ ]

- **Bearings**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to [ ]

- **Substructure**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to [ ]

- **Inventory Rating**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to [ ]

- **Posting**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to [ ]

- **Other** – Please provide any items that you feel should have been included but were not, along with any additional comments.

Impact on Public Component

- **Deck Geometry**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **Underclearances – Horizontal and Vertical**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **Approach Roadway Alignment**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **Detour Length**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **ADT and ADTT**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **STRAHNET Designation**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **Bridge Railing**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **Posting**

  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **Other** – Please provide any items that you feel should have been included but were not, along with any additional comments.

Hazard Resistance Component

- **Scour Critical**
  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to
- **Channel and Channel Protection**
  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to
- **Waterway Adequacy**
  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to
- **Seismic Zone**
  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to
- **Seismic Design**
  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to
- **Structure Type**
  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to
- **Underclearances – Horizontal and Vertical**
  ☐ Agree ☐ Disagree - Remove ☐ Disagree - Move to

- **Other** – Please provide any items that you feel should have been included but were not, along with any additional comments.

APPENDIX E – PARTICIPANT SOLICITATION E-MAIL FOR RELATIVE WEIGHTS

Thank you very much for allotting some of your valuable time to participate in the first part of this study. Your responses along with over 45 other colleagues representing 28 states were used to identify the items for each bridge management component. Items were selected by tallying the responses and then keeping, removing or moving each item based on the majority of the responses. Now that items have been determined, we would appreciate if you could please take time to participate in the second (and last) part of the survey by first reading the document entitled *Relative Weights.pdf* and then completing the corresponding Excel file attached to this e-mail by following the simple instructions found in the *Relative Weights.pdf* document.

I have attached 2 versions(you only need to complete **one** of the versions) of the Excel spreadsheet, *Relative Weights (2003).xls* for participants using 2003 and earlier versions and *Relative Weights (2007).xlsx* for participants using 2007 and newer versions. Please complete this portion of the survey and send the appropriate spreadsheet via e-mail to jhnsn@rams.colostate.edu by **June 17, 2011**.

Sincerely,
Joshua Johnson
Co-Principal Investigator

APPENDIX F – INSTRUTIONS FOR RELATIVE WEIGHTS

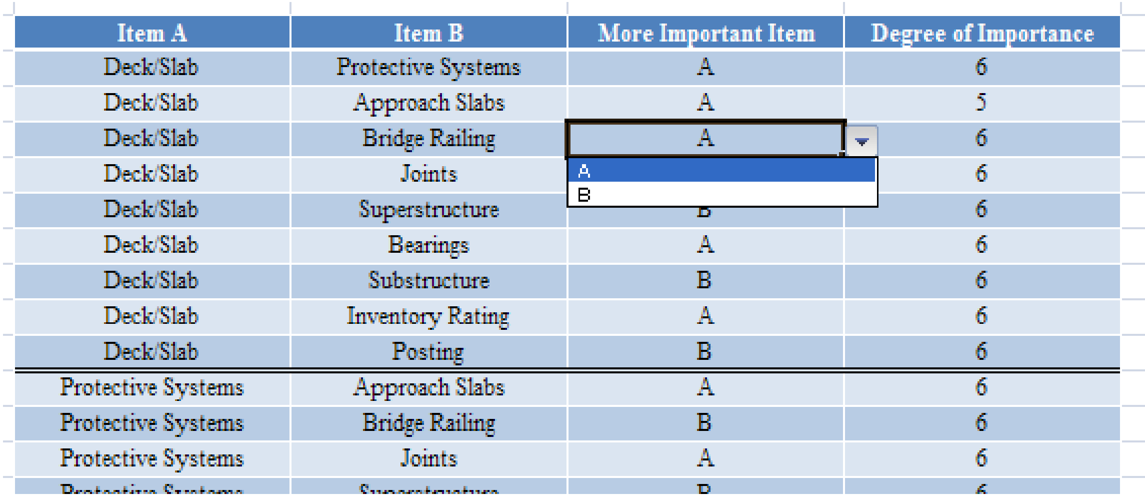
IDENTIFYING ITEMS' RESPECTIVE RELATIVE WEIGHTING VALUES

Please fill out the attached Excel spreadsheet, which will be used to determine each item's importance relative to the other items in defining each bridge management component. In the spreadsheet, you will be making paired comparisons and judge which item is more important along with the degree of that importance. This survey is a part of a structured decision process called the Analytic Hierarchy Process (AHP), which will be used to assign a quantitative value (i.e. a weight) to each item under each bridge management component.

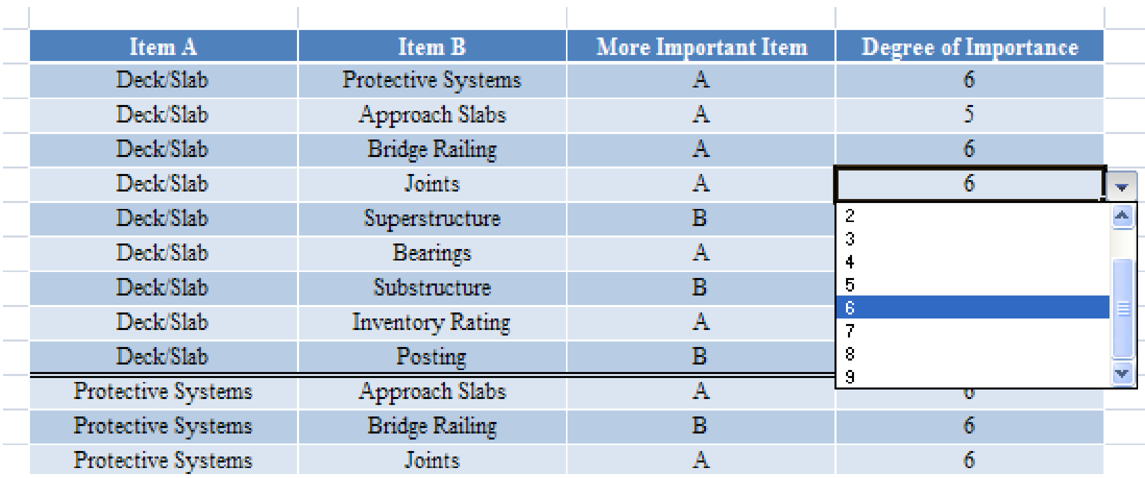
As an example, if the two items being compared are *superstructure* and *approach slabs*, you may feel that the *superstructure* is more important than the *approach slabs* in achieving the defined objective of the structural condition bridge management component. The degree of that importance is based on a 1 through nine 9 scale. See the following table for the definition, explanation and guidance of how convert your judgments to a numerical value.

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two criteria contribute equally to the objective
2	Slightly More Important	
3	Moderate Importance	Experience and judgment slightly favor one criteria over another
4	Moderate to Strong Importance	
5	Strong Importance	Experience and judgment strongly favor one criteria over another
6	Strong to Very Strong Importance	
7	Very Strong Importance	A criteria is strongly favored and its dominance is demonstrated in practice
8	Very, Very Strong Importance	
9	Extreme Importance	The evidence favoring one criteria over another is of the highest possible order

Given the table and your judgment, you feel the degree of the *superstructure's* importance over the *approach slabs* is very strong, and so you would assign a value of 7. The following figures provide an example of how make your judgments and assign a degree of importance, using the drop down selection boxes in the Excel spreadsheet.



Item A	Item B	More Important Item	Degree of Importance
Deck/Slab	Protective Systems	A	6
Deck/Slab	Approach Slabs	A	5
Deck/Slab	Bridge Railing	A	6
Deck/Slab	Joints		6
Deck/Slab	Superstructure	B	6
Deck/Slab	Bearings	A	6
Deck/Slab	Substructure	B	6
Deck/Slab	Inventory Rating	A	6
Deck/Slab	Posting	B	6
Protective Systems	Approach Slabs	A	6
Protective Systems	Bridge Railing	B	6
Protective Systems	Joints	A	6
Protective Systems	Superstructure	B	6



Item A	Item B	More Important Item	Degree of Importance
Deck/Slab	Protective Systems	A	6
Deck/Slab	Approach Slabs	A	5
Deck/Slab	Bridge Railing	A	6
Deck/Slab	Joints	A	6
Deck/Slab	Superstructure	B	
Deck/Slab	Bearings	A	
Deck/Slab	Substructure	B	
Deck/Slab	Inventory Rating	A	
Deck/Slab	Posting	B	
Protective Systems	Approach Slabs	A	6
Protective Systems	Bridge Railing	B	6
Protective Systems	Joints	A	6

In addition to comparing items under each bridge management component in the first 3 sheets in the Excel file, please take a few minutes to complete the last sheet to perform paired comparisons between different bridge management components and judge which component is more important than the other concerning prioritizing bridges for preservation and improvement work.

Please complete this portion of the survey and return the appropriate spreadsheet via e-mail to jhnsn@rams.colostate.edu by **June 17, 2011**. Again, it is very much appreciated that you are taking valuable time to participate in this part of the survey. This is the final part of this survey and your input will be invaluable in finalizing this study.

APPENDIX G – SUMMARY OF PARTICIPANT COMMENTS

TABLE OF COMMENTS FROM PROPOSED ITEMS SURVEY – SORTED BY PARTICIPANT

Participant 1	• *Protective Systems:* [Comment] Paint, deck protection systems, cathodic protection systems etc., are not a structural (load carrying) component. They do however affect the durability (useful life) of a bridge. Suggest moving to Hazard Resistance with the environmental degradation the hazard. • *Approach Slabs:* [Move to] Impact on Public. Again approach slabs are not a structural component but help move the "bump" away from the bridge and may provide temporary access should the approach embankment be lost during a flood or earthquake. • *Bridge Railing:* [Move to] Impact on Public. Not a structural component but safety feature used to protect the public. • *Joints:* [Comment] Not a structural component. Not sure Hazard? • *Inventory Rating:* [Move to] Impact on public. Not a structural component but a result of structural adequacy. In [our State] many bridges with low inventory ratings are adequate for the loads they see. • *Posting:* [Comment] See Inventory above • *Waterway Adequacy:* [Move to] Impact on public. Deals with frequency of approach roadway flooding.
Participant 2	• *Impact on Public:* [Add Item] Add capacity • *Hazard Resistance:* [Comment] Seismic zone and design are listed as indicators of a potential seismic risk. These indicators are vague (Design) or crude (Seismic zone) approximations of the potential vulnerability.
Participant 3	• *Impact on Public:* [Add Item] Operating Rating impacts routing of overweight permitted vehicles • *Hazard Resistance:* [Add Item] Vulnerability to ship impact and vulnerability to storm surge
Participant 4	• *Structural Condition:* [Add Item] Type of Repair • *Impact on Public:* [Add Item] School Bus • *Hazard Resistance:* [Add Item] Unknown Foundation and Fracture Critical

Participant 5	• *Structural Condition:* [Add Item] Culvert • *Impact on Public:* [Add Item] Bridge roadway width.
Participant 6	• *Protective Systems:* [Add new] preservation component [and move to said component] • *Joints:* [Add new] preservation component [and move to said component] • *Structural Condition:* [Comment] Suggest creating a 4th component for preservation ... include paint, joints, channel protection, wearing surface, cathodic protection, etc.
Participant 7	• *Impact on Public:* [Add Item] Is this structure contributing to this being a high accident location on the system
Participant 8	• *Structural Condition:* [Comment] The superstructure should also have protective systems similar to the deck. • *Hazard Resistance:* [Comment] It might be clearer if the seismic design was moved to the Structural Condition section. In major rehabilitations, we always try to address any seismic issues.
Participant 9	• *General Comment:* Honestly, I fail to see the usefulness of this questionnaire or the research project in general. The NBI already identifies practically all of the non-structural items. Pontis, probably the most commonly used BMS software, identifies the structural components via the Core Elements. I'm just unclear what this adds that isn't already available.
Participant 10	• *Structural Condition:* [Comment] Need another category for "Maintenance Needs" for some items. Deck should be included in this category also.
Participant 11	• *Structural Condition:* [Add Item] Turndown or end diagrams [diaphragms?] on semi-integral abutment, which is part of superstructure at the support (abutments or piers). • *Impact on Public:* [Comment] ADT is also an important factor to determine the adequacy of bridge width and functional obsolete bridges
Participant 12	• *General Comment:* Overall, not sure I understand the complete premise here. Is this research effort an attempt to replace such Bridge Management/Bridge Inventory information as Sufficiency Rating, Health Index, SD/FO, etc. with a new scheme? A bit more background and some examples of the better share the vision would be helpful. Also, I believe you may benefit from the addition of an additional choice in each of these Items; that being "Not Sure". It is difficult to make some of these choices, without fully understanding and appreciating how the selections chosen may affect the operational capability

	of the resulting BMS.
Participant 13	• ***Structural Condition:*** [Add Item] Age, year built
Participant 14	• *Structural Condition:* [Comment] Slabs more greatly influence ride-ability, comfort etc. Only a total deck failure would affect structural capacity. Approach slabs are not part of the bridge and certainly not structural. [Our State] does track Item 67 Structural Condition, which encompasses the poorest rating of 58, 59, 60, 62 and Inventory Rating Item 66. • *Hazard Resistance:* [Comment] Scour critical channel and channel protection and waterway adequacy go hand in hand and could be one item. [We are] in the lowest hazard area for EQ so it is not a concern here.
Participant 15	• *Impact on Public:* [Comment] Bridge Railing also shows up in the Structural Condition Components
Participant 16	• *Hazard Resistance:* [Add Item] Bridge Railing
Participant 17	• *Structural Condition:* [Add Item] Operating Rating and Culvert should be included. • *Impact on Public:* [Comment] STRAHNET is a military mobility component - does not belong with Impact on Public.
Participant 18	• *Structural Condition:* [Comment] Superstructure should be divided out between the different types, i.e., Steel, Pre-stressed Concrete Girders, PT /PS Spliced Concrete girders. • *Deck Geometry:* [Comment] I would be more concerned with the roadway approach onto the bridge. Is there adequate approach guardrail and approach treatments. • *Waterway Adequacy:* [Comment] I would think that this information could be captured under the channel and channel protection category. • *Hazard Resistance:* [Comment] I believe an issue with the potential for scour that you could potentially capture with the channel/channel protection would also be if the waterway is migrating in one direction or another that could ultimately impact the roadway approaches or undermine the existing substructure elements.
Participant 19	• *Deck / Slab:* [Comment] Deck & Slabs should be separate. • *Superstructure:* [Comment] This is a sum of components, not a component. Useful to calibrate to NBI. • *Substructure:* [Comment] this is a sum of components, not a component. Useful to calibrate to NBI.

	• *Structural Condition:* [Add Item] Concrete Deck Soffit: This condition is independent of the top surface. Concrete Deck's primary function amounts to tracking deterioration. Timber & steel decks are a structural evaluation. Slabs are also condition but more important than decks since they are the superstructure. • *Deck Geometry:* [Comment] Items listed should be evaluated separately. Vertical Clear should be handled with Underclearance. • *Approach Roadway Alignment:* [Comment] Include with Design and Safety standards.
Participant 20	• *Structural Condition:* [Comment] Should Inventory Rating be moved to Impact on Public Component, or maybe placed in both?
Participant 21	• *Protective Systems:* [Comment] Should include steel coating • *Structural Condition:* [Comment] If you are only interested in evaluating the structural integrity of the bridge, then I believe all of the identified items are essential in the structural evaluation process. However, if you're interested in evaluating the preservation replacement and improvement needs, then you will need information on all bridge elements. A good source of a comprehensive list of bridge elements is the newly released AASHTO guide manual for bridge element inspection, first edition, 2011. • *Bridge Railing:* [Comment] Applies from safety perspective • *Impact on Public:* [Add Item] Waterway adequacy (frequent flooding) will also impact the bridge use by the public • *Hazard Resistance:* [Add Item] Fracture Critical and fatigue prone details should be considered
Participant 22	• *Structural Condition:* [Comment] I am not sure that an inventory rating or posting is [are?] a true measure of bridge adequacy. We need to move away from structural deficiency or adequacy. Need to define state of good repair, or good fair poor. • *Impact on Public:* [Comment] Public needs to understand, a perfectly good wooden bridge is NOT a bad bridge, and a POSTED bridge is not a bad bridge either. • *Hazard Resistance:* [Comment] As a highway engineer, I am not as comfortable discussing water clearances, etc.
Participant 23	• *Structural Condition:* [Comment] Would remove joints & rails UNLESS it was more specific, e.g., deck condition within the development length of the steel from the joint/railing? Otherwise, except for impact to the railing, these

	are mostly irrelevant to the load path, and therefore more maintenance issues than structural issues per se. • *Impact on Public:* [Add Item & Comment] Joints & end of bridge - if that "bump" is severe enough, it can damage tie-rods, etc. Underclearance (horizontal and vertical) influences the utility of the structure to the public. • *Hazard Resistance:* [Comment] Seismic design & seismic zone should be combined into "seismic adequacy." Including structure type really implies some sort of unlisted hazard, which has greater impact on certain structure types. Better to look at the hazard and have a resistance assessment for that. Underclearance and channel protection should be related to some sort of hazard, e.g., collision hazard.
Participant 24	• *Structural Condition:* [Add Item] Remaining Bridge Service Life, Proposed or Scheduled Improvements • *Impact on Public:* [Add Item] Pedestrian access (i.e. ADA Compliance), Utilities on Structure (i.e. Illumination and ITS) • *Hazard Resistance:* [Add Item] Vessel Collision Protection, Anti-Terrorism Design and Hardening
Participant 25	• *Impact on Public:* [Add Item] School Bus routes should be added.
Participant 26	• *Structural Condition:* [Comment] Joints, bearings and approach slabs might be better defined or split upon what ails them. If it is a riding issue across a joint, it could be under Impact on Public. If it is a structural distress causing a safety issue with traffic, then it could be under Structural Condition or a new Safety section. A weighted amount could be used based on the cost of repair, or a separate BMS decision based on repair needs of this issue on its own merit. So, you would not replace the bridge if the joint(s) were bad, you would replace/repair the joint. The same decision making ability could/should be used for the deck and possibly the superstructure, provided the substructure is adequate into the foreseeable future. The paint condition and the ability to apply a coating that will continue to protect should be considered. As an example, if you have a truss with packrust between the built up section members, you cannot maintain a coating that will continue to protect the bridge elements. You can protect for a very short duration, and then the packrust continues. • *Impact on Public:* [Comment] Deck Geometry - graded on how much it actually restricts traffic flow, tied to ADT. Underclearances only based on how the restrict traffic flow or limit vehicles based on VC or HC. Approach

	Roadway Alignment - only for severe cases that restrict traffic flow. ADT and ADTT only based on current or projected Level of Service, again based on ability to convey traffic. STRAHNET - No. Should be based on serviceability. ADT and ADTT concerns already convey how important the route is. Railing - Based solely on safety rating. There could be a separate section on safety and include railing type/height, joint ride-ability, narrow bridge (severe deck geometry deficiencies), severe approach roadway alignments, scour criticality, very low postings (where one might believe overloaded vehicle use could collapse bridge, etc., and removed from this section. • *Hazard Resistance:* [Comment] Underclearances - prorated on how restrictive / probability of impact / consequences. Seismic Design should trump seismic zone - if a bridge is designed to handle zone, then OK.
Participant 27	• *Impact on Public:* [Add Item] Overclearances (horizontal and vertical), maybe relation to corridor projects, maybe "other" category for customization. • *Hazard Resistance:* [Add Item] Consider blank item for future customization
Participant 28	• *Structural Condition:* [Add Item] Include wearing surface with protective system. • *Impact on Public:* [Add Item] Use NHS designation in place of STRAHNET.
Participant 29	• *Structural Condition:* [Add Item] Foundation Types • *Impact on Public:* [Add Item] Traffic Signs • *Hazard Resistance:* [Add Item] Environment
Participant 30	• *Impact on Public:* [Add Item] NHS or not' might be good to include. • *Hazard Resistance:* [Add Item] Fracture criticality, and structural material type. Plus consider moving Deck Geometry to this group since it is tied to likelihood of collisions.
Participant 32	• *Structural Condition:* [Add Item & Comment] I would suggest adding the Structural Evaluation Item (67) which is important to consider if the bridge is designed to carry the loads it is seeing whether it's in perfect condition or not (i.e. deterioration). Also depending on how the different items above are used (including item 67), it may be worth considering whether the Structural Deficient Code was triggered (i.e. the SD/FO Status, but consider FO in the Impact of Public Component). Age of the bridge may also be a factor worth considering, depending on how it's used/weighted in the BMS. Age could play a factor in both the condition and public impact components; see my comments below.

	• *Impact on Public:* [Add Item & Comment] Besides what I mentioned above about using the FO (Functionally Obsolete) trigger in this Component, the Bridge Age may also be a factor in this Impact on Public component more from a Historical sense. In trying to develop a BMS for [our agency], I consider most of the items you listed in the Public Impact Component as "Socio-Economic" impacts and I agree with them. What I mean by "Socio-Economic" is that bridge priorities may be influenced by the more obvious "Economic" impacts that you've identified above, but there are also Social Impacts (Heritage, Culture, & potentially Political). In other words, the public may have certain "feelings" about a bridge, especially if its Structure Type is "Signature" or its Age is potentially "Historical". Political may be a stretch, but unfortunately considering where bridges are relative to certain Districts can and does have impact on priority whether Engineers want to consider it or not.
Participant 33	• *Structural Condition:* [Comment] Posting may also be due to under design. But this one is tricky, because if the bridge is, for example, on a parkway where there are not trucks, it may be posted even though that posting has not effect of serviceability of the bridge. • *Impact on Public:* [Add Item] Perhaps deck condition should be included here, since this can affect the drivability of the deck.
Participant 34	• *Protective Systems:* [Comment] BME in new AASHTO guide • *Superstructure:* [Comment] Differentiate more I think • *Substructure:* [Comment] Differentiate more I think • *Inventory Rating:* [Comment] dubious value - too many rating methods. This number seems suspect a lot in the State inventories • *Posting:* [Comment] Maybe. Can be a political value. Posting in particular seems very dubious.... Structural condition might be terrific but it is still posted because of original design strength. • *Detour Length:* [Comment] If realistic • *Impact on Public:* [Comment] ADT numbers are squirrelly especially for future years. Hard to rely on this data, as it usually comes from a traffic section that is often behind in their traffic counts.